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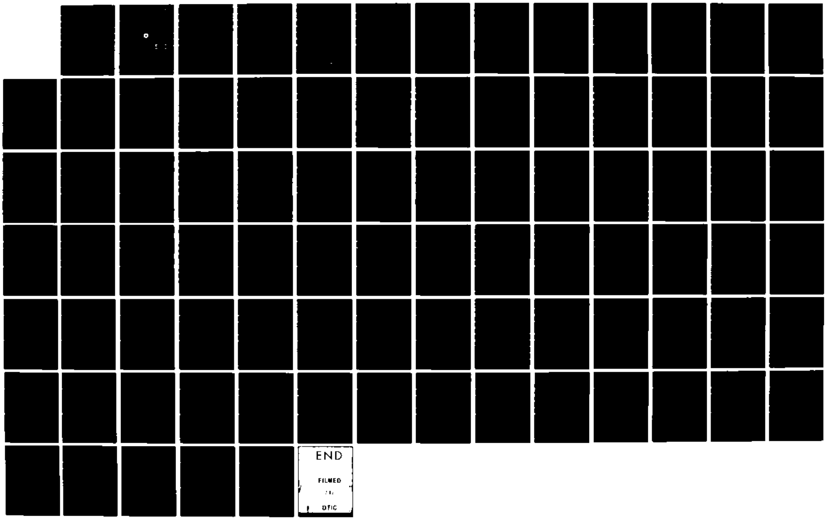

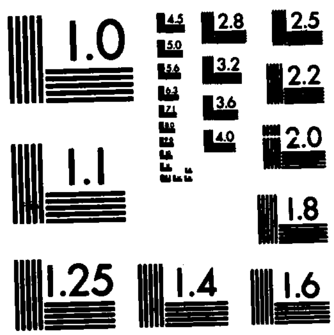
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AN ANALYSIS OF REPORTS OF OPERATIONAL ERRORS

Trans Systems Corporation
Vienna, Virginia

August 1982

Prepared for:

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Office of Aviation Safety
Washington, DC 20591

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16. Abstract

The findings of the statistical analyses used to determine whether the level of safety performance within the air traffic control system was affected by the air traffic controllers' strike of August 1981 are presented. The analysis of the operational errors reported during specified periods before and after the August 3, 1981, strike provided statistical confirmation regarding the lack of degradation of national airway safety after the strike. The post-strike operational errors normalized to the volume of operations are shown to be lower than the normalized operational errors reported in the period prior to the strike.

The operational errors and operation volume data covered the periods from January 1980 to February 1982 for monthly analyses and from January 1980 to April 1982 for weekly analyses.

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PREFACE

An analysis of reports of operational errors was performed by Trans Systems Corporation under the sponsorship of the Office of Aviation Safety, Federal Aviation Administration.

The study attempts to determine through various statistical methods whether the level of performance within the air traffic control system was affected by the air traffic controllers' strike of August 1981.

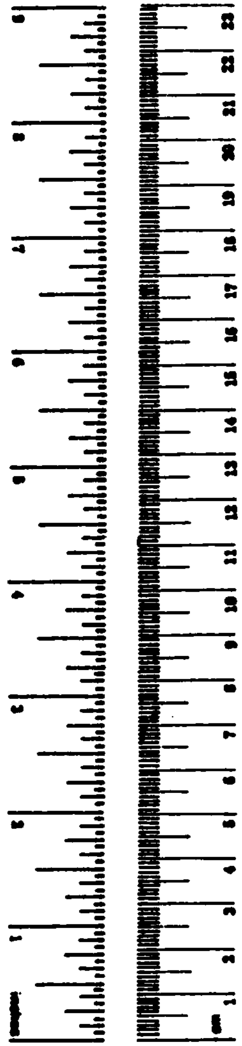
The principal authors are Dr. Mallik Arjunan, Eric Longstreet, and John C.H. Woo. Review was provided by Dr. S. Chowdhury and Mr. Walter Faison of Trans Systems Corporation. Messrs. Ross Gaisor and Jon Roché assisted in the data summary.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

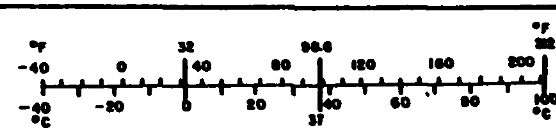
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

Past studies conducted by the National Transportation Safety Board (NTSB) and the Flight Safety Foundation (FSF) have indicated that safety has not been compromised in the post-ATC strike environment. This report summarizes the results of a study sponsored by the Office of Aviation Safety aimed at the quantitative assessment and comparison of the level of safety of the ATC system, both before and after the air traffic controllers' strike.

This effort focuses on "operational errors" as a surrogate in assessing the safety of the ATC system. This is not to say that other parameters and approaches may not also be appropriate in this regard; however, "operational errors" was chosen since it directly relates to controllers' errors, and good pre- and post-strike data were available.

This report is limited to the treatment of operational error data. The existence of qualifying circumstances and considerations, such as the possible over-reporting of operational errors before the strike and/or the under-reporting of such errors after the strike, are neither accepted nor rejected. They are simply not dealt with in this report.

The frequency of operational errors and the volume of operations at FAA centers and towers formed the statistical basis for our various analyses. Operational errors are recorded on a daily basis and were summarized for our use into weekly and monthly frequency counts along with those corresponding numbers of operations.

Our first level of study simply compared the absolute numbers of operational errors for a fixed period before the strike data of August 3, 1981, to a similar period after that date. The results of that comparison follow:

	Terminal Operational Errors	Center Operational Errors	Total Errors
Pre-Strike Period (August 9, 1980, to April 25, 1981)	278	171	449
Post-Strike Period (August 9, 1981, to April 25, 1982)	139	99	238

This approach in itself is insufficient for firm conclusions since it does not take into account the lower level of operations experienced in the post-strike environment. The next step was to introduce the simple concept of a rate. This was done by comparing the number of errors per million operations for the selected pre-strike period to a similarly selected post-strike period. Those results are as follows:

	Terminal Operational Error Rate (Errors/Million Operations)	Center Operational Error Rate (Errors/Million Operations)	Total
Pre-Strike Period (August 9, 1980, to April 25, 1981)	6.131	12.793	18.924
Post-Strike Period (August 9, 1981, to April 25, 1982)	3.883	8.301	12.184

This approach, however, does not deal with the notion that reduced operational levels normally lead to reduced rates of conflict (operational errors per million operations). Therefore, we postulated a predictable relationship between operational errors and volume of operations using statistical regression techniques. We were not able to support the postulation, however, because the available data for errors and operations resulted in the generation of inadequate correlation coefficients. Nonetheless, we were able to determine that the post-strike error rates were significantly lower than the pre-strike rates.

In summary, our analyses showed the following:

- There were fewer operational errors in the post-strike period than in the pre-strike period, both for terminals and air route traffic control centers.
- The rate of operational errors (per million operations) was lower in the post-strike period than in the pre-strike period, both for terminals and air route traffic control centers.
- The difference in the operational error rates between the pre-strike and post-strike study periods could not be attributed to chance.

The findings support the view that the national airspace system is at least as safe in the post-strike period as in the pre-strike period.

1.0 BACKGROUND

1.1 History

On August 3, 1981, a strike by the air traffic controllers against the FAA resulted in the loss of nearly 11,400 of the nation's air controller work force, at that time totalling about 17,275 persons. In the weeks and months following the strike, there was concern in the aviation community as to whether there was safety degradation in the nation's air terminals and air route traffic control centers.

On December 8, 1981, the National Transportation Safety Board (NTSB) released a special report[1] on post-strike air safety. The report, titled "Special Investigation Report - Air Traffic Control Systems," stated that the ATC system "was operated safely in the two months following the strike," noting that operational errors decreased in the post-strike period. Moreover, it stated that "no basic ATC procedures were changed or compromised in order to keep the ATC system in operation, and the high level of ATC safety required is possible within the present system and will be possible as the system is rebuilt."

Another independent investigation conducted by the Flight Safety Foundation (FSF) basically supports the conclusions of the NTSB. The FSF was commissioned by the Office of the Administrator (FAA) in August 1981 to make a safety appraisal of the post-strike ATC system. Its findings,[2] released on January 29, 1982, concluded that the ATC system as it existed from September

[1] National Transportation Safety Board, "Special Investigation Report - Air Traffic Control System," NTSB-SIR-81-7, Washington, DC, December 1981.

[2] Flight Safety Foundation, "A Safety Appraisal of the Air Traffic Control System," Report No. FSF-ATC-1142-8-82U. Contract No. DTFA01-81-C-10109k January 29, 1982.

through November 1981, maintained a level of safety equivalent to that of the pre-strike system.

1.2 Purpose of this Study

The FAA Office of Aviation Safety sponsored this study aimed at the quantitative assessment of the level of safety of the air traffic control (ATC) system before and after the August 3, 1981, strike. A second objective was to analytically compare those assessments in an effort to determine whether any degradation in the post-strike ATC environment could be observed. The ultimate goal of this work is either to confirm the earlier independent efforts or to pinpoint system weaknesses (if they exist) and consider alternative actions for remediation.

1.3 Alternative System Parameters for Potential Use in Assessing the Safety of the ATC System

A number of alternative system parameters come to mind in any discussion of the safety of the ATC system. These include operational errors, near mid-air collisions, mid-air collisions, and system delays.

"Operational Errors" was chosen as the most likely surrogate to analyze the ATC system since it directly bears on safety, reflects controller performance, has readily available pre-strike and post-strike data, and is restricted in where it occurs to only "controlled" airspace. No other alternative parameters satisfied all of these requirements to the same extent as did "operational errors."

1.4 Reporting Operational Errors

The FAA defines an operational error as an occurrence which results in less than the applicable separation minima between two or more aircraft, or between an aircraft and terrain or obstacles (e.g., vehicle on runway). These separation minima are defined in the FAA Handbook 7110.65 or its supplemental instructions.

Whenever an operational error is thought to have occurred, authorized FAA personnel are required to report the incident immediately to their supervisor. Once reported, the incident is investigated to determine the cause or reason for the error and is classified within one of three categories: (a) human error, (b) procedural error, or (c) equipment error.

The report resulting from the investigation is reviewed by the Regional Air Traffic Division and is then forwarded to the Air Traffic Service Evaluation Group, AAT-20, located in Washington, DC. This AAT-20 group compiles the occurrences of operational errors on a daily basis and maintains a file on all operational error reports.

2.0 ANALYTICAL METHODS

2.1 Operational Error Magnitudes and Rates

Data were first collected on the frequency of operational errors, both before and after the August 3, 1981, strike. This information was obtained for terminals and centers separately. Additionally, operational activity levels were identified for the same pre- and post-strike periods. Initially, the data were collated by month and analyzed, but the analysis did not yield conclusive results (see Appendix B). The data were collated by week, the summary of data consisting of 54 weeks of the pre-strike period and 38 weeks of the post-strike period. Tables 2-1 and 2-2 summarize these raw data.

From these tables we find the following:

- The magnitude of operational errors before the strike at the terminal areas [$\Sigma\ E^{T}_{(2-1)}$] exceeded the magnitude of operational errors after the strike at those same locations for an equal period of time [$\Sigma\ E^{T}_{(2-2)}$].*
- Similarly, the magnitude of operational errors before the strike at the 20 contiguous centers [$\Sigma\ E^{C}_{(2-1)}$] exceeded the magnitude of operational errors after the strike at those same locations for an equal period of time [$\Sigma\ E^{C}_{(2-2)}$].*

Since the number of operations was also down at these terminals and centers, such results were not unexpected or conclusive in themselves. The change in "rate" of operational errors was therefore analyzed next. The following results were obtained.

- The rate of operational errors/million operations was down in the terminal areas in the post-strike period compared to the pre-strike period:

---

* E = Operational Error, T = Terminal, C = Center

Table 2-1. Summary of Weekly Operational Errors and Totals of Operations for the 54-Week Pre-Strike Period

Observations	Week Ending			Weekly Terminal Data		Weekly ARTCC Data	
	Year	Month	Day	Number of Operational Errors	Number of Operations	Number of Operational Errors	Number of Operations
1	80	07	26	8	1,352,799	5	362,506
2	80	08	02	9	1,358,872	5	364,536
3	80	08	09	6	1,363,836	8	363,780
4	80	08	16	2	1,316,787	8	375,314
5	80	08	23	7	1,352,514	4	369,951
6	80	08	30	11	1,328,418	5	368,569
7	80	09	06	7	1,237,996	6	327,584
8	80	09	13	7	1,324,598	6	354,718
9	80	09	20	10	1,317,307	3	364,695
10	80	09	27	8	1,318,066	7	354,013
11	80	10	04	12	1,281,525	9	351,639
12	80	10	11	7	1,300,875	6	346,397
13	80	10	18	8	1,242,335	5	349,962
14	80	10	25	13	1,292,284	6	354,055
15	80	11	01	7	1,245,811	5	353,277
16	80	11	08	11	1,246,481	2	352,361
17	80	11	15	5	1,172,455	4	358,701
18	80	11	22	6	1,232,380	2	363,345
19	80	11	29	6	968,501	1	303,959
20	80	12	06	11	1,091,588	7	356,617
21	80	12	13	7	1,137,857	4	353,145
22	80	12	20	6	1,062,626	9	357,159
23	80	12	27	5	799,796	2	270,933
24	81	01	03	2	854,096	3	265,395
25	81	01	10	3	1,029,650	2	343,019
26	81	01	17	8	1,078,408	2	352,545
27	81	01	24	5	1,183,023	3	359,304

Table 2-1 (Continued)

Observations	Week Ending			Weekly Terminal Data		Weekly ARTCC Data	
	Year	Month	Day	Number of Operational Errors	Number of Operations	Number of Operational Errors	Number of Operations
28	81	01	31	6	1,154,359	5	359,126
29	81	02	07	7	1,077,425	3	346,338
30	81	02	14	8	1,037,724	1	345,157
31	81	02	21	8	1,160,091	3	351,608
32	81	03	28	9	1,191,761	4	364,701
33	81	03	07	11	1,154,765	6	365,331
34	81	03	14	8	1,335,057	5	367,500
35	81	03	21	6	1,190,992	2	363,982
36	81	03	28	11	1,308,798	5	370,383
37	81	04	04	5	1,160,948	6	354,638
38	81	04	11	5	1,285,477	5	370,815
39	81	04	18	5	1,275,588	1	366,720
40	81	04	25	9	1,230,191	6	370,116
Subtotals	(August 9, 1980, to April 25, 1981)			$\Sigma E^T = 278$	$\Sigma (Ops)^T =$ 45,342,389	$\Sigma E^C = 171$	$\Sigma (Ops)^C =$ 13,366,852
41	81	05	02	6	1,339,795	3	368,208
42	81	05	09	2	1,313,424	5	370,426
43	81	05	16	10	1,243,427	3	369,757
44	81	05	23	7	1,337,481	3	364,226
45	81	05	30	3	1,209.934	2	342,938
46	81	06	06	9	1,275,974	4	368,339
47	81	06	13	7	1,297,597	5	371,427
48	81	06	20	10	1,329,766	9	375,405
49	81	06	27	3	1,341,642	6	367,292
50	81	07	04	5	1,224,539	1	348,930
51	81	07	11	8	1,333,605	6	368,835
52	81	07	18	8	1,375,848	7	379,143
53	81	07	25	7	1,334,841	3	382,091
54	81	08	01	7	1,367,052	5	379,767
Grand Total				$\Sigma E^T = 387$	$\Sigma (Ops)^T =$ 66,378,985	$\Sigma E^C = 243$	$\Sigma (Ops)^C =$ 19,250,678

Table 2-2. Summary of Weekly Operational Errors and Totals of Operations for the 38-Week Post-Strike Period

Observations	Week Ending			Weekly Terminal Data		Weekly ARTCC Data	
	Year	Month	Day	Number of Operational Errors	Number of Operations	Number of Operational Errors	Number of Operations
1	81	08	09	5	1,026,821	2	151,928
2	81	08	16	3	1,029,535	4	296,278
3	81	08	23	1	1,084,494	0	300,420
4	81	08	30	7	1,024,875	1	314,899
5	81	09	06	4	956,322	2	313,748
6	81	09	13	3	1,081,767	2	296,836
7	81	09	20	3	1,043,951	3	322,152
8	81	09	27	2	1,041,570	0	315,861
9	81	10	04	7	1,017,633	1	307,632
10	81	10	11	5	988,306	1	322,581
11	81	10	18	5	977,371	3	317,368
12	81	10	25	3	996,004	4	309,152
13	81	11	01	4	974,927	2	320,651
14	81	11	08	3	1,042,270	5	318,332
15	81	11	15	3	1,034,113	1	305,051
16	81	11	22	7	966,210	1	324,695
17	81	11	29	4	832,958	1	287,035
18	81	12	06	4	939,048	4	317,320
19	81	12	13	1	918,741	2	327,470
20	81	12	20	3	843,955	4	336,426
21	81	12	27	1	675,975	3	269,214
22	82	01	03	4	699,635	2	275,094
23	82	01	10	2	792,856	6	309,690
24	82	01	17	2	711,920	1	297,857
25	82	01	24	5	755,992	2	314,908

Table 2-2(Continued)

Observations	Week Ending			Weekly Terminal Data		Weekly ARTCC Data	
	Year	Month	Day	Number of Operational Errors	Number of Operations	Number of Operational Errors	Number of Operations
26	82	01	31	1	903,222	4	325,510
27	82	02	07	7	872,295	2	321,273
28	82	02	14	1	895,543	2	331,152
29	82	02	21	3	907,173	4	334,237
30	82	02	28	1	1,016,397	6	336,999
31	82	03	07	5	934,631	2	334,855
32	82	03	14	3	946,053	6	345,522
33	82	03	21	3	926,723	4	350,860
34	82	03	28	6	1,028,634	2	342,442
35	82	04	04	2	877,033	2	334,589
36	82	04	11	5	902,465	2	317,561
37	82	04	18	6	1,049,618	6	342,802
38	82	04	25	5	1,083,617	0	335,632
Grand Total				$\Sigma E^T = 139$	$\Sigma (Ops)^T =$ 35,800,653	$\Sigma E^C = 99$	$\Sigma (Ops)^C =$ 11,926,032

$$\left[\frac{\Sigma\, E^{T}_{(2-2)}}{\Sigma\, Ops^{T}_{(2-2)}} \text{ versus } \frac{\Sigma\, E^{T}_{(2-1)}}{\Sigma\, Ops^{T}_{(2-1)}} \right]^{*} : \left[\frac{139}{35.801} = 3.883 \text{ versus } \frac{278}{45.342} = 6.131 \right]$$

- Similarly, the rate of operational errors/million operations was down in the 20 centers during the post-strike period compared to the pre-strike period:

$$\left[\frac{\Sigma\, E^{C}_{(2-2)}}{\Sigma\, Ops^{C}_{(2-2)}} \text{ versus } \frac{\Sigma\, E^{C}_{(2-1)}}{\Sigma\, Ops^{C}_{(2-1)}} \right]^{*} : \left[\frac{99}{11.926} = 8.301 \text{ versus } \frac{171}{13.367} = 12.793 \right]$$

Even with such reductions in operational error rates, one could still argue that conclusions regarding the comparative safety of the ATC system could not be made. The argument goes something like this: When a significant reduction in operations takes place, then the "expected number" of conflicts (operational errors) also goes down, but not proportionally -- it goes down geometrically. Therefore, the next step is to set out to establish a predictable relationship between errors and operations using regression techniques.

2.2 Regression Techniques to Establish a Relationship Between Errors and Operations

The approach adopted for the analysis of the operational error data was based on the primary assumption that the number of reported operational errors will decrease with a decrease in the number of operations (exposure). The analysis attempts to relate volume of operations and operational errors for both pre-strike and post-strike periods by computing the predicted operational errors for the post-strike period (based on pre-strike observations) and comparing the predictions with the reported post-strike errors.

* Ops = Number of Operations in Millions

If the predicted operational errors are statistically equal to or above the error levels observed during the post-strike period, then one could conclude that safety was reasonably maintained following the controllers' strike. Through plotting the data, a preliminary examination of points revealed that the relationship between operational errors and number of operations appear to be linear. This finding is consistent with an earlier study by Lyman[1] in which a simple linear regression using the formulation:

$$y = b_o + b_1 x$$

showed a high correlation square (R^2) between operational errors (y) and the predictor variable x (number of operations) with the value of the F ratio shown to be highly significant.

The analysis of the operational error data as a function of the number of operations handled by each of the two control areas was due to the constraints imposed by the data. There were no other data whose variability was considered to have a significant effect on the number of reported operational errors. In other words, reliable data on other potential contributing factors were not available. Thus, the initial analytical approach was to use a simple linear regression model of the form: $Y = a + bX$. This was done using the logarithmic transformed data.

However, the results of these simple linear regressions gave reason to attempt further analysis by regressing the data in time lag periods (i.e., t, t-1, t-2, and t-3) such that an estimate of parameters might be obtained

[1] Lyman, E.G., "ATC Contingency Operations in the En Route Flight Regime," NASA CR-(166231), Battelle Memorial Institute, 1981.

using an autoregressive procedure. The model used in this autoregression contains a time-series part as well as a systematic (ordinary least-squares) part and approximates the following formulation:

$$E_t = bV_t + \alpha_t$$

where

$$\alpha_t = \varepsilon_t - a_1 \alpha_{t-1} - a_2 \alpha_{t-2} - a_3 \alpha_{t-3}$$

The error term of this linear model is assumed to follow a third order autoregressive process. The error factor, ε, is assumed to be normally and independently distributed with mean zero and variance (σ^2).

On obtaining the results of the autocorrelation using the linear autoregression model, the output is used to estimate parameters which are linear. This output was used in the nonlinear regression to achieve an estimate of the residual sum of squares between the predicted and observed data points. The details of the analytical model are shown in Appendix A.

2.3 Test of Significance of Proportion

In comparing the data from the pre-strike and post-strike periods, it becomes important to make statistical comparisons between the proportions associated with the populations of the two periods. The population proportion used for comparison of these periods is the operational error rate, expressed as the proportion of operational errors per number of operations.

These operational error rates are computable for each observation and for each set of observations (i.e., towers and centers, pre-strike and post-strike). The difference between any observed proportions (e.g., $p_1 - p_2$) of two independent samples can then be compared to determine whether or not the proportions (i.e., error rates) for the pre-strike and post-strike periods came from the same population (i.e., the differences between rates were due to random chance).

For sufficiently large populations (n_1, $n_2 > 30$), the sampling distribution of $p_1 - p_2$ is approximately normally distributed (and the covariance between the errors and the volume of operations can be assumed to be zero) with a mean equal to $p_1 - p_2$ and a standard error of:

$$\sqrt{\left(\frac{p_1 + p_2}{n_1 + n_2}\right) (q) \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$$

Therefore, when the null hypothesis is that of "no difference" between the two populations to be tested, the test statistic will be Fisher's "z" determined from the formula:

$$z = \frac{p_1 - p_2}{\sqrt{pq \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

Thus, the computation of rates will determine whether the operational errors from the post-strike period normalized to the volume of operations are the "same as" or "lower than" the normalized operational errors reported from the pre-strike period, expressed with an acceptable level of significance.

3.0 ANALYSIS OF WEEKLY DATA

3.1 Data Reduction

As an attempt to improve the results derived earlier from the monthly summary data, it was decided to examine the operational errors data using expanded weekly counts. Hence, the daily records of operational errors and operations handled were summarized into weekly compilations from airport towers (terminals) and air route traffic control centers (ARTCC) for both the pre-strike and post-strike periods. The new summary (presented in Tables 2-1 and 2-2) consisted of 54 weeks in the pre-strike period and 38 weeks in the post-strike period (where additional data from March and April 1982 were available).

The pre-strike data used in this new summary consist of 54 weekly frequency counts of operational errors and operations reported from July 20, 1980, through August 1, 1981. These pre-strike weeks were taken from Sunday through the following Saturday (i.e., a normally defined week). However, since the strike began on Monday, August 3, 1981, the post-strike weeks were taken from Monday through the following Sunday, encompassing a post-strike period from August 3, 1982, through April 25, 1982. The data collected on Sunday, August 2, 1981, were eliminated from the summary. The plots of operational errors by week are shown in Appendix E.

3.2 Linear Regression Analysis

3.2.1 Transformations

Regression analysis was performed on the weekly operational errors data, using as many as five different transformations of the data. Transformations were used to change the original variable (particularly the independent variable) to new variables for which the standard regression assumptions are more closely satisfied.

The three primary reasons for using data transformations are (1) to stabilize the variance of the dependent variable when the homogeneity assumption is violated; (2) to normalize (i.e., to transform the normal distribution) the dependent variable when the normality assumption is noticeably violated; and (3) to linearize the regression model when the original data suggests a model that is nonlinear in either the regression coefficients and/or the original variables (dependent or independent). Very often the same transformation will simultaneously help to accomplish the first two goals and sometimes the third.

The types of transformation used are:

a. Log transformation ($y = \log x$): used when the relationship of dependent variable (operational errors) with the independent variable suggests a model with a consistently increasing slope.
b. Reciprocal transformation ($y = \frac{1}{x}$): used to minimize the effect of large values of dependent variable, since the transformed values will be close to zero, and large increases in the dependent variable will only cause trivial decreases in transformed values.
c. Arcsin transformation ($\sin^{-1} (\frac{y}{x}) = x$): used when a dependent variable is a proportion or rate, in this case, the operational error rate (i.e., errors divided by operations).

d. Square transformation ($y^2 = x$): used when a dependent variable increases with a decreasing slope.

e. Constant multiplicand transformation ($2y = x$): used when the dependent variable increases at a constant proportion to the independent variable (in this case, the constant is 2).

3.2.2 Results of the Pre-Strike Data

A simple regression analysis was performed on the various transformations of the data, using the general linear formulation:

$$\text{error} = \beta + (a)\ \text{operations}$$

where "β" is the intercept at zero operations and "a" is the slope. (See Appendix D.) The results of these regressions are presented in Table 3-1, which includes the correlation coefficients (r) and other important statistics for both towers and centers for the pre-strike and post-strike periods.

The pre-strike untransformed data for towers yielded a correlation coefficient (r) of 0.2495 and for centers an "r" of 0.1024, neither of which were significant at the 0.05 level.

In general, the various transformations did not substantially improve these results. The log-transformed data for towers yielded an "r" of 0.1285 and for centers an "r" of 0.2966. This correlation for the centers data was shown to be significant at the 0.05 level, indicating that for the center data the relationship between the operational errors and volume of operations is barely predictable using a log-linear model. For the centers data, the volume of operations is much less than for the towers data and the log transformation would alter the variance such that the coefficient of correlation would improve.

Table 3-1 Results of Correlation Analysis Between Operational Errors (Y) and Volume of Operations (X)

Transformation Type	Terminals		ARTCCs	
	Pre- (n=54)	Post- (n=38)	Pre- (n=54)	Post- (n=38)
1. (Untransformed): (errors) = (ops)	r = 0.2495 $\bar{x}$ = 1228870 σ_x = 127733 α = 0.0000 $\bar{y}$ = 7.1666 σ_y = 2.5679 β = 1.002	r = 0.2057 $\bar{x}$ = 0.942 σ_x = 0.1085 α = 3.504 $\bar{y}$ = 3.658 σ_y = 1.849 β = 0.357	r = 0.1024 $\bar{x}$ = 356484.1 σ_x = 21881.28 α = 353617.17 $\bar{y}$ = 5.019 σ_y = 3.9214 β = 571.27	r = 0.2249 $\bar{x}$ = 314000.84 σ_x = 32874,17 α = 302781.17 $\bar{y}$ = 2.6053 σ_y = 1.7169 β = 4306.54
2. Log: (errors) = $\log_{10}$ (ops)	r = 0.1285 $\bar{x}$ = 6.1055 σ_x = 0.1490 α = 2.2148 $\bar{y}$ = 7.1666 σ_y = 2.5679 β = -6.3561	r = 0.0936 $\bar{x}$ = 5.59982 σ_x = 0.1770 α = 0.9777 $\bar{y}$ = 3.6579 σ_y = 1.8474 β = 2.2066	r = 0.2966* $\bar{x}$ 5.5507 σ_x = 0.0296 α = 5.5322 $\bar{y}$ = 4.5000 σ_y = 2.1346 β = 0.0041	r = 0.157 $\bar{x}$ = 5.493 σ_x = 0.058 α = 5.479 $\bar{y}$ = 2.605 σ_y = 1.717 β = 0.005
3. Reciprocal: (errors) = $\frac{1}{(ops)}$ $[10^{-6}]$	r = 0.2737 * $\bar{x}$ = 0.8241 σ_x = 0.1044 α = 6.7338 $\bar{y}$ = 7.1666 σ_y = 2.5679 β = 12.7159	r = -0.2184 $\bar{x}$ = 1.0773 σ_x = 0.1420 α = 2.8444 $\bar{y}$ = 3.6579 σ_y = 1.8494 β = 6.7223	r = -0.3035 $\bar{x}$ = 2.8178 σ_x = 0.2109 α = 2.9527 $\bar{y}$ = 4.5000 σ_y = 2.1346 β = -0.003	r = - 0.150 $\bar{x}$ = 2.605 σ_x = 1.717 α = 4.026 $\bar{y}$ = 3.243 σ_y = 5.892 β = 4.381

* Significant at 0.05 level

Table 3-1 (Continued)

Transformation Type	Terminals Pre- (n=54)	Terminals Post- (n=38)	ARTCCs Pre- (n=54)	ARTCCs Post- (n=38)
4. Arcsin: $\sin^{-1}(\frac{errors}{ops}) = (ops)[10^{-5}]$	r = 0.0149 $\bar{x}$ = 12.2920 σ_x = 1.2785 α = 0.0776 $\bar{y}$ = 11.7542 σ_y = 6.6775 β = 10.8002	r = 0.0337 $\bar{x}$ = 9.4092 σ_x = 1.076 α = 9.3608 $\bar{y}$ = 20.3068 σ_y = 15.2016 β = 0.0024	r = -0.222 $\bar{x}$ = 3.5648 σ_x = 2.188 α = 3.4599 $\bar{y}$ = 12.5575 σ_y = 5.815 β = 8.3599	r = 0.0755 $\bar{x}$ = 8.305 σ_x = 5.260 α = 6.472 $\bar{y}$ = 3.229 σ_y = 7.001 β = 5.67
5. Square: $(errors)^2 = (ops)[10^{-4}]$	r = 0.2164 $\bar{x}$ = 123.0500 σ_x = 12.7610 α = 0.6313 $\bar{y}$ = 58.2040 σ_y = 37.2210 β = -19.4760	r = 0.1975 $\bar{x}$ = 94.2122 σ_x = 10.8573 α = 91.7857 $\bar{y}$ = 16.7368 σ_y = 14.7862 β = 0.1450	r = 0.2599 $\bar{x}$ = 35.6484 σ_x = 2.1881 α = 34.9786 $\bar{y}$ = 24.7222 σ_y = 20.9954 β = 0.0271	r = 0.2576 $\bar{x}$ = 31.400 σ_x = 11.046 α = 17.523 $\bar{y}$ = 9.658 σ_y = 3.287 β = 0.866
6. Constant Multiplicand: $(errors)\,2 = (ops)[10^{-4}]$	r = 0.2515 $\bar{x}$ = 122.9224 σ_x = 12.7842 α = 0.1010 $\bar{y}$ = 14.3330 σ_y = 5.1359 β = 1.9153	r = 0.2066 $\bar{x}$ = 94.2123 σ_x = 10.8573 α = 89.7757 $\bar{y}$ = 7.3158 σ_y = 3.6988 β = 0.6064	r = 0.3162* $\bar{x}$ = 35.6484 σ_x = 2.1881 α = 34.1899 $\bar{y}$ = 9.000 σ_y = 4.2692 β = 0.1621	r = 0.1218 $\bar{x}$ = 5.9417 σ_x = 5.2237 α = 0.1647 $\bar{y}$ = 31.4575 σ_y = 3.2775 β = 0.1941

* Significant at the 0.05 level

The reciprocal transformation was shown to improve the correlation for both the terminal and the center data, "r" equals 0.2737 and -0.3035, respectively. The reciprocals tend to minimize the variance in the independent variable. This appears to increase the covariance to variance ratio, raising the coefficient of correlation. For the center data, the negative correlation and the negative slope show that the errors decrease at an increasing rate of operations.

The square transformation and the constant multiplicand transformation both raised the coefficient of correlation for the center data to a significant level. And the β is shown to improve from the square transformation to the constant multiplicand transformation.

In summary, the center data appears to show that the relationship between operational errors and the volume could be predictable. Such a relationship is less apparent from the tower data.

3.2.3 Results of the Post-Strike Data

None of the "r" values are significant in the post-strike period. The reciprocal transformation does show an improvement in the "r" values but it is not sufficient to be significant. The lack of significant correlation suggests that the relationship between the operational errors and the volume of operations is not well defined. However, the proportion of errors per million operations could be tested to reveal whether or not the rate of operational errors could vary as the volume of operations. A test of significance of proportions was performed, and the results are shown in the following section.

3.3 Test of Significance of Error Rates

Regardless of the fact that the results of the linear regressions did not yield significant relationships between the two variables for pre-strike and post-strike data sets, a test of significance of operational error rates can be made to determine whether or not the drop in the number of observed errors during the post-strike period is significant. Since the volume of operations also dropped during that post-strike period, the question becomes "Has there been a proportionate decrease in the errors corresponding to the decrease in volume of operations?"

The error rate per million operations would normalize the errors by dividing into the appropriate volume of operations. Again, the average error rate in the post-strike period is lower than in the pre-strike period. This in itself does not substantiate evidence that it might be expected based on the proportion of errors in the population. Further, it should be shown that the difference in rates is the one that can be obtained based on the difference between the pre-strike and post-strike periods, and not due to chance.

The test of proportions selected for this comparison between populations was Fisher's "z" distribution, in which the parameters to be tested are the proportions of errors per volume of million operations (details of this test are presented in Appendix D).

The "z" test was performed for the weekly data. The null hypothesis tested was $H_o: p_b = p_a$ meaning no difference in error rates between "before" and "after" the strike. The alternative hypothesis tested $H_a: p_b < p_a$, that is, the error rate is less in the post-strike period than in the pre-strike period.

When the towers and centers data were separately tested for the difference between the pre-strike and post-strike periods, the values obtained were 3.310 and 11.537, respectively.

Since these "z" values were significant at the 0.01 level, the conclusion was to reject the null hypothesis and retain the alternative hypothesis. The result of this test supports the conclusion that the difference in error rates between the two periods is more than what could be expected by chance and that the system, as measured by operational error rates, was safer in the post-strike period than in the pre-strike period.

In addition, a test was conducted to test the difference in error rates between the towers and centers within the same period -- pre-strike and post-strike periods. In both the pre-strike and post-strike periods, the center error rates were higher than the tower error rates. In both, the "z" values were higher, -3.384 in the pre-strike period and -5.267 in the post-strike period, thus resulting in rejection of the null hypothesis. The conclusion is that the center error rates were larger than the tower error rates and the difference is more pronounced in the post-strike period than in the pre-strike period.

4.0 DISCUSSION OF RESULTS

This study attempted to establish the relationship between operations and operational errors. While in general there are statistical findings between the two variables, the present study, because of a lack of sufficent monthly data, could not firmly establish a relationship. A further detailed study was undertaken by expanding that data (i.e., using weekly data instead of monthly data) for both the pre-strike and post-strike periods. The importance of adding more data points to improve the relationship is evidenced by an overall data analysis (which pooled pre- and post-strike data points), and is presented in Appendix C. The rationale for pooling the data was an attempt to investigate whether post-strike data caused any drastic change in the relationship which existed between operational errors and operations from the post-strike period.

When the data were regressed using an autoregressive lag model, the least-squares estimates were nonlinear. The estimates show that the variables are related and that the estimates of coefficients are inversely correlated. This alone does not categorically establish that the errors are smaller in the post-strike period than in the pre-strike period, but it does show that the residual errors are negative and the observed errors then are smaller in size and distance from the estimated errors.

However, this study is a result of analysis of data only, and the conclusions should be limited to that extent. A study based on a survey of errors and the various treatment effects (such as human errors, procedural errors, or equipment errors) probably reveal further cause and effect relationships of operational errors. The study by Battelle (Lyman) established a relationship. This study shows that if a model based on lagged regressors is adopted, the least-squares estimates would have to be nonlinear, and this would render a more generalized estimate of coefficients than ordinary least-squares estimates.

Further analysis of the weekly summary data basically supported the findings of the analysis of the monthly summary data, in that the coefficients of correlations were somewhat high enough to establish a statistically valid relationship between operational errors and volume of operations.

When the weekly data were analyzed extending the rate concept further using the test of significance based on the "z" test, the results showed that the rate of the pre-strike period was larger than the rate in the post-strike period and that the difference was statistically noteworthy. Thus, this test provides a basis for believing that the system has fewer errors in the post-strike period and can be rated safer relative to the pre-strike period.

However, it should be borne in mind that the error rate is only one of the measures that is being used in this analysis. If safety could be measured as a result of multiple factors, such as operational errors, near mid-air collisions, system difficulty reports and other parameters, then a more comprehesive performance measurement of safety performance of the system could be made, a comprehensive performance measurement that would facilitate long-term predictions or forecasting.

The conclusions reached by this study are at best tentative, since there was no attempt to isolate the cause of errors and the source of variance, such as type of operation. A study of field operations would be useful.

Moreover, it is feasible to suggest that the working conditions surrounding the strike itself were responsible for an apparent drop in operational error reports for a number of reasons, not the least of which could be the existence of unreported errors during the hectic period following the strike. Further, it is the opinion of some observers that tension among ATC personnel during the period preceding the strike could have caused a higher reporting rate of operational errors during that time.

In addition, the study took into account only one exposure variable -- namely, volume of operations. There are many factors besides traffic volume (e.g., number of hours flown by pilot, aircraft miles flown, number of aircraft hours flown) that would have certainly influenced the number of reported operational errors during the period under analysis, and which may, when used singularly or in combination, offer an improved correlation with operational errors.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conc' ısions

In summary, the analysis of the operational errors reported during the specified periods before and after the August 3, 1981, air traffic controllers' strike provides statistical confirmation that national airway safety was not adversely affected after the strike. Conclusions of the analysis are as follows:

a. Post-strike operational errors normalized to the volume of operations (error rate) are shown to be statistically lower than normalized operational errors reported in the period prior to the strike, using a test of significance of proportions.

b. Pre-strike operational error data from centers and towers appeared to show some correlation (though the correlation is inadequate for prediction purposes) between operational errors and number of operations using a simple linear regression model with specific transformations.

c. Neither the post-strike operational error data from the terminals or those from the centers appeared to show a significant relationship between errors and operations using a simple linear regression model.

5.2 Recommendations

Observations made during the course of this analysis have contributed to the following recommendations:

a. Useful by-products generated by this analysis are the readily available daily operational errors and corresponding operation volume data, which can be used to identify peak and nonpeak levels of operational error occurrences by such categories as weekdays, weekends, and holidays, along with monthly, seasonal, and annual fluctuations. In view of the very limited research done on the operational errors and operation activity, it would be useful to study and examine further what hazard exposure parameters affect the occurrence of operational errors. Since airway incident reports (such as operational errors, aircraft accidents, and near-miss collisions) are functions of various risk exposure (such as aircraft delay, number of operations, pilot hours, aircraft miles, and aircraft hours), further analysis would serve to identify and clarify exposure/incident relationships.

b. As independent test cases, certain towers and centers should be selected where the system was stable (known technology coefficient or factors) and these could be used as a representative sample by geographical location or type of activity. These individual case studies would provide the insight and necessary steps to enlist more representative samples for extrapolation to a national level -- bottom-up. The results of this approach could be checked against the top-down method using predicted operational errors only based on nationwide total statistics.

c. The exponential relationship between operational errors and traffic volume could be further investigated and validated. For example, the decrease in the number of operational errors has been shown to be greater (exponentially related) than the decrease in the number of operations -- meaning that if the number of operations is reduced by half, the errors could be reduced by more than half.

d. Continue work on operational error categorization which deals with additional raw data. This involvement will provide more expanded opportunity for safety analysis.

e. Perform additional statistical analysis and prepare associated graphical representations separately for centers and towers as well as combined data with descriptive statistics, such as mean, standard deviation, etc. As a result of such analysis, it will be possible to make a visual comparison of pre-strike and post-strike periods using the absolute number of operational errors.

f. Enhance familiarity with available raw data and data base functions, and establish a monitoring program relating to any variation in data by group of hours, areas, mode of operation, etc. This effort must also include a readiness to undertake a limited full scale analysis in the areas of human errors, hardware errors, and procedural errors.

STATISTICAL APPENDICES

A. ANALYTICAL MODELS

B. ANALYSIS OF MONTHLY DATA

C. OVERALL DATA AND TIME SERIES ANALYSIS

D. COEFFICIENT OF CORRELATION AND TEST OF PROPORTION

E. PLOTS OF OPERATIONAL ERRORS BY WEEK

APPENDIX A. ANALYTICAL MODELS

The model for the simple linear regression, the autoregressive model, and the methods relevant to non-linear least squares estimates of the parameters used are presented below:

A.1 Linear Model

Let E denote the operational errors and V the volume of operations, then $E = \beta \log V + \alpha$. (1) is the model which would describe the relationship betweeen the two variables, α, β being coefficients of the model commonly referred to as intercept and slope, respectively.

In the case of regression,

$$(E - \overline{E}) = r \frac{\sigma_E}{\sigma_V} (V - \overline{V})$$

or

$$E = r \frac{\sigma_E}{\sigma_V} (V - \overline{V}) + \overline{E} \qquad (2)$$

This can be readily seen as (1) (the equation (2) reduces to (1))

if $r \frac{\sigma_E}{\sigma_V} = \beta$, $(V - \overline{V}) = \log V$ and $\overline{E} = \alpha$

which is a linear function.

In the ordinary least squares (OLS) estimation of parameters, the partial derivatives are minimized. If $\log V = V^*$, then partial derivatives are minimized.

$$\frac{\partial}{\partial_V} (E - \beta V^* - \alpha)^2 = 0 \qquad (3)$$

However, if both the pre-strike data and post-strike data were put into one data base, the autocorrelations have to be verified.

A.2 Autoregressive Model

$$E = V\beta$$

is the basic model. When the time series regression model is assumed, it becomes

$$E_t = V_t\beta + \alpha_t \qquad (4)$$

where

$$\alpha_t = \varepsilon_t - a_1\alpha_{t-1} - a_2\alpha_{t-2} \cdots\cdots a_k\alpha_{t-k}$$

and ε_t are i. i. d. $N(0, \sigma^2)$.

$a_1 \ldots a_k$ are autoregressive parameters.

To obtain estimates of the parameters $a_1 \ldots a_k$ the following equations of Yule-Walker form are solved.

$$\text{Toep } [r_o \ldots\ldots r_{k-1}]\ a = [r_1 \ldots r_k]$$

$[r_1 \ldots r_k]$ is a k x 1 vector of autocovariances and Toep is Toeplitz operator.

All the variables are transformed in the following way. The first k observations are transformed using the form:

$$[Z_1 \ldots Z_k]^T = \hat{\sigma}P\ [V_1 \ldots V_k]^T$$

The remaining observations are transformed using the autoregressive model

$$Z_t = V_t + \sum_{i=1}^{k} a_i V_{t-i} \qquad (5)$$

β the regression parameter that is estimated in the OLS form.

The model used to obtain least-squares estimates of regression coefficients is in the following form:

$$E = B_o + B_1 (V) + R^2 (E_{t-1} - B_o - B_1 (V_{t-1})) \qquad (6)$$

This is nonlinear in form. Therefore, nonlinear linear squares estimation is needed.

A.3 Nonlinear Estimation of Parameters

As in the linear model, the nonlinear linear squares estimation proceeds with $E = F (B_o, B_1 \ . \ . \ . \ V_1, V_2) + \varepsilon = F(B) + \varepsilon$

The normal equations are

$V'F (B) = V'E$ where $V = \partial F/\partial B$

The solution is necessarily iterative and after an initial value is chosen for B, and its estimated value is improved until $\hat{\varepsilon}'\hat{\varepsilon}$ (error sum of squares) is minimized.

The Gauss-Newton method uses expansion of Taylor series

$$F(B) = F (B_o + V (B - B_o) + V' (V - B_1) + \dots)$$

where

$$V = \left. \frac{\partial F}{\partial B} \right|_{B_o}$$

This series substituted in the normal equations will yield

$$V' F(B) = V'E$$

$$V' [F(B_o) + V(B-B_o)] = V'E$$

$$V' F(B_o) + V'V(B-B_o) = V'E$$

$$V'V(B-B_o) = V'E - V'F(B_o)$$

$$= V'(E-F(B_o)$$

$$= V'e$$

$$(B-B_o) = (V'V)^{-1}V'e.$$

$$\Delta = (V'V)^{-1}V'e$$

This proceeds until $\hat{\varepsilon}'\hat{\varepsilon}(B_o + k\Delta) < \hat{\varepsilon}'\hat{\varepsilon}(B_o)$.

However, in estimating B_o, B_1 in Equation (6), we need a derivative-free method, because the variables in the function do not satisfy the properties of continuous function. The algorithm called DUD[1] (Doesn't Use Derivatives) was used to estimate using least-squares procedure. It is essentially a modified Gauss-Newton algorithm. The procedure is as follows:

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[1]Ralston, M and Jennrich, R. "DUD, Derivate-Free Algorithm for Non-Linear Least Squares," Technometrics, February 1978, p7-14.

The least squares begins with minimizing the sum of the squares of a parameter B

$$F(B) = \sum_{i=1}^{n} (V_i - f_i\ (B))^2 \quad \text{for n observations}$$

$$= \| V_i - F_i\ (B)\|^2 \qquad (7)$$

Step 1. Let $B_1^m \ldots . B_{p+1}^m$ p = no. of parameters to be estimated

m = no. of iterations

2. $F\ (B) \sim \ell^m(B)$

3. Find $\hat{B}^m \ni \min D\ \overline{\ell(B)-E}$

4. $\hat{B}^m \leftarrow B_i^m : B_i^{m+1}$, $i = 1 \ldots . p+1$ in m+1 iterations

$$B = B_{p+1} + \Delta\ B\,\alpha, \qquad (8)$$

B_1, $B_2 \ldots . B_{p+1}$ are estimates from prior iterations.

The linear approximation is given by

$\ell(\alpha) = f\ (B_{p+1}) + \Delta F\alpha$, where

i^{th} column, $\Delta F_i = f(B_i) - f(B_{i+1})$

One iteration consists of minimizing function

$$\tilde{Q}(\alpha) = (e-\ell(\alpha))' (e-\ell(\alpha)).$$

The solution is

$$\alpha = (\Delta F'\Delta F)^{-1} \Delta F(e-f(B_{p+1}))$$

Then this value is entered into Equation (8) to obtain $\hat{B}$. This iteration stops when ESS is minimum or no reduction in ESS is found when convergence is assumed.

APPENDIX B. ANALYSIS OF MONTHLY DATA

B.1 Data Reduction

The daily records of operational errors reported separately from airport towers (terminals) and air route traffic control centers (ARTCC) were totalled for all user categories (i.e., Air Carrier, General Aviation, Air Taxi/Commuter, and Military). These daily error counts were summed to get monthly error compilations for the 19-month pre-strike (January 1980 through July 1981) and the seven-month post-strike (August 1981 through February 1982) periods.

The number of operations handled per month was required for use in the analysis. The operations data were obtained from the Office of Aviation Policy and Plans (APO), received as daily frequency counts for combined user types, from each controlled airspace (i.e., terminals and ARTCCs). The monthly operation totals were compiled separately for the 19 pre-strike months and the seven post-strike months.

The monthly operation totals were recorded in millions of operations, a form that does not offer much suitability for analysis. Therefore, the totals were re-expressed before analysis, using the transformation function of logarithm to the base of 10 (i.e., common logarithm) since it is divisible into a million. By transforming the monthly operation totals into this form, the operational error data and the operations data take on a more symmetric form.

Tables B-1 and B-2 present the operational errors data for the pre-strike and post-strike periods, respectively. The pre-strike data consist of 19 monthly frequency counts of operational errors reported throughout the year 1980 and on up to July 1981. The post-strike data consist of seven monthly frequency counts of operational errors that were reported from the post-strike

Table B-1. Summary of Monthly Operational Errors and Totals of Operations for the 19-Month Pre-Strike Period

Observations	Year	Month	Monthly Terminal Data		Monthly ARTCC Data	
			Number of Operational Errors	Number of Operations (logs)	Number of Operational Errors	Number of Operations (logs)
1	80	1	27	6.67783	13	6.40183
2	80	2	25	6.68695	16	6.38324
3	80	3	25	6.73504	17	6.41151
4	80	4	37	6.75239	24	6.38532
5	80	5	30	6.75960	19	6.40599
6	80	6	24	6.76087	13	6.39727
7	80	7	45	6.77563	23	6.41019
8	80	8	26	6.76844	28	6.41858
9	80	9	37	6.74960	24	6.39628
10	80	10	41	6.75243	28	6.41082
11	80	11	30	6.69588	10	6.36119
12	80	12	29	6.64916	23	6.37774
13	81	1	22	6.68011	13	6.39196
14	81	2	32	6.65054	11	6.36100
15	81	3	39	6.73862	21	6.41859
16	81	4	24	6.73713	18	6.41303
17	81	5	26	6.75198	15	6.41471
18	81	6	31	6.75200	26	6.41584
19	81	7	33	6.77137	18	6.43675

Table B-2. Summary of Monthly Operational Errors and Totals of Operations for the Seven-Month Post-Strike Period

Observations	Year	Month	Monthly Terminal Data		Monthly ARTCC Data	
			Number of Operational Errors	Number of Operations (logs)	Number of Operational Errors	Number of Operations (logs)
1	81	8	17	6.66654	8	6.33689
2	81	9	15	6.64835	6	6.34059
3	81	10	21	6.64056	11	6.36089
4	81	11	19	6.61581	9	6.33167
5	81	12	10	6.57027	14	6.34973
6	82	1	13	6.53264	13	6.33707
7	82	2	13	6.56794	15	6.33069

data of August 1981 through February 1982. The monthly counts are separated for terminals (airport towers) and ARTCCs (cer'ers).

In addition to the monthly operational errors, the tables provide the monthly totals of terminal operations and ARTCC operations expressed in their common logarithms [i.e., log (V), where V is the monthly total of operations].

On examining the data provided in these tables, it is evident that the operational errors generally appear to decrease as the totals of operations decrease, in a rather monotonic fashion for both terminals and centers. And even while the number of operations per month shows a decline after the August 1981 date, the relationship between the monthly operational errors and the monthly operations, both for the terminals and the centers, appears to have a similar pattern to the relationship shown in the pre-strike period.

B.2 Linear Regression Analysis

B.2.1 Methodology

The initial analysis of the data was made using a simple linear regression model of the form:

$$E_i = b_1 \log (V_i) + b_o$$

where

E_i is monthly operational errors, and

V_i is monthly operations handled.

In this simple data fitting procedure, using the method of least-squares to estimate the parameter, the objective is to find the values of the constants in the above equation that minimize the sum of the squared deviations of the observed values from those predicted by the equation.

The least-squares estimates of b_o and b_1 are those values of b_o and b_1 which minimize the function:

$$Q = \sum_{1}^{N} (E_i - b_1 \log (V_i) - b_o)^2$$

The estimates of b_o and b_1 and the estimate of the variance, σ^2, are obtainable through the use of regression procedures, using the method of ordinary least-squares. And later, using the autoregressive process, the autocorrelation of lag coefficients and their covariance are estimable by means of an autoregression procedure, which first estimates the model $E = bV$ using the method of ordinary least-squares and then computes the autocorrelation up to lag = 3 of the residuals from the ordinary least-squares regression.

B.2.2 Results of Pre-Strike Period

The results of the simple regression on the 19 pre-strike tower observations using the linear model:

$$\text{Errors} = K \log (\text{Operations}) + C$$

show that only 12 percent ($R^2 = 0.1191$) of the variance in operational errors is explained by the linear model using volume of operations as the only predictor variable. This weak linear relationship is reflected by the low value (2.30) of the F ratio, shown only to be significant at the 0.15 level.

The corresponding results on the 19 pre-strike center observations, while shown to be slightly better than those reported for the tower data, still did not evidence a strong linear relationship between operational errors and number of operations. In this case, 20 percent of the variance in operational errors could be explained by the linear model with the computed F value of 4.18 shown only to be significant at the 0.10 level.

The best linear models for each data group, based on the estimates using the simple regression procedure, were as follows:

For Tower Data: $E = 54.27 \log (\text{Ops}) - 334.47$

For Center Data: $E = 126.45 \log (\text{Ops}) - 790.41$

The standard deviation for each group of data ($s = 6.27$ for the tower data and 5.24 for the center data) was found to be quite large for an $n = 19$.

Based on these results, the linear model used for these regressions appears to have been insufficient to describe the data, so an autoregression model using time lag coefficients was tried in order to achieve a better data fit.

Using a specified lag order of $t = 3$, the resulting model took the form:

$$E_t = bV_t + \alpha_t$$

Where

E_t is the number of operational errors at a given time

V_t is the (log) volume of operations at a given time

b is the regression coefficient, and

α_t is the autoregression coefficient.

The results of the autogression on the tower data using this modified linear model are presented in Table B-3 and show that the autocorrelations of the residuals from the ordinary least-squares regression appear to change sign after the second lag ($t=2$). Note that in the autocorrelation procedure used, the second order lag coefficient was set equal to zero (i.e., $a_2 = 0$). And, the covariance of the estimated b values with E_t is shown to be 0.05.

Table B-3. Results of Autoregression on the Pre-Strike Tower Data

<u>Model</u>: $E_t = bV_t + \varepsilon_t - a_1\alpha_{t-1} - a_2\alpha_{t-2} - a_3\alpha_{t-3}$

1. <u>Ordinary Least Squares Estimates</u>

Variable	Degree of Freedom	b Value
(Intercept)	0	0
V_t	1	4.5670

2. <u>Estimates of Autocorrelations</u>

Lag	Covariance	Correlation
0	39.1352	1.0000
1	-7.0614	-0.1804
2	-7.3376	-0.1875
3	7.7618	0.1983

Bar Chart of Autocorrelations

```
-1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1
 |                    |********************|
 |                ****|                    |
 |                ****|                    |
 |                    |****                |
```

Table B-3 (Continued)

3. Estimates of the Lag Coefficients

Lag	Coefficient	Std. Deviation	t Ratio
1	0.1484	0.2263	0.6558
3	-0.1704	0.2263	-0.7531

Error Terms

Sum of Squares (SSE)	670.5215
Deg. of Freedom (DFE)	17
Mean Square (MSE)	39.4424
Root Mean Square (Root MSE)	6.2803

4. Estimate of b-Value

Variable	DF	b-Value	Std. Deviation	t Ratio	Approx. Prob.
Intercept	0	0	0		
V_t	1	4.5830	0.2209	20.743	0.0001

5. Covariance of b-Value

	Intercept	V_t
Intercept	0	0
V_t	0	0.0488

The estimates for the time-lag coefficients produced the model:

$$\alpha_t = \varepsilon_t - 0.0474\ \alpha_{t-1} + 0.0458\ \alpha_{t-3}$$

Performing similar procedures on the pre-strike center data (see Table B-4), the results of the systematic part of the autoregressive process showed the covariance of the b values with E_t to be 0.04.

And the results of the time-series part yielded an autogression coefficient of:

$$\alpha_t = \varepsilon_t - 0.0474\ \alpha_{t-1} + 0.0458\ \alpha_{t-3}$$

B.2.3 Results for Post-Strike Period

When the post-strike data were analyzed using the simple linear regression, neither the tower data nor the center data showed a strong linear relationship between the two parameters. For the tower data, about 45 percent ($R^2 = 0.4539$) of the variance in operational errors could be explained by the model using volume of operations, while only 0.2 percent ($R^2 = 0.0022$) of the variance in center operational errors were explainable using the volume of center operations.

These findings were reflected by their corresponding low F values, which were significant only at the 90 percent and the 10 percent confidence levels, respectively.

This weak linearity could have been expected since the pre-strike data did not fit a similar linear model. However, because the post-strike data only consists of five observations (after deducting the two degrees of freedom), it could not be examined as a separate universe by applying autocorrelation procedure.

Table B-4. Results of Autoregression on the Pre-Strike Center Data

<u>Model</u>: $E_t = bV_t + \varepsilon_t - a_1\alpha_{t-1} - a_2\alpha_{t-2} - a_3\alpha_{t-3}$

1. Ordinary Least-Squares Estimates

Variable	DF	b-Value
(Intercept)	0	0
V_t	1	2.9613

2. Estimates of Autocorrelations

Lag	Covariance	Correlation
0	30.2969	1.0000
1	-1.4066	-0.0464
2	0.6644	0.0219
3	1.3574	0.0448

Bar Chart of Autocorrelations

```
-1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1
 |                    |********************|
 |                   *|                    |
 |                    |                    |
 |                    |*                   |
```

Table B-4 (Continued)

3. Estimates of the Lag Coefficients

Lag	Coefficient	Std. Deviation	t Ratio
1	0.0474	0.2289	0.2071
3	-0.0458	0.2289	-0.2002

Error Terms

Sum of Squares (SSE)	571.1357
Deg. of Freedom (DFE)	17
Mean Square (MSE)	33.5962
Root Mean Square (Root MSE)	5.7962

4. Estimate of b-Value

Variable	DF	b-Value	STD Deviation	t Ratio	Approx. Prob.
(Intercept)	0	0	0		
V_t	1	2.9649	0.2072	14.304	0.0001

5. Covariance of b-Value

	Intercept	V_t
Intercept	0	0
V_t	0	0.0429

B.3 Non-Linear Regression Analysis

B.3.1 Methodology

After estimating lagged independent regressions, the least-squares estimators were used to estimate the residuals between the predicted and observed data points. This comparison of residuals will serve to illustrate how well the residuals converge to give good estimates of the parameters.

While there are many iterative methods that could be used to obtain non-linear least-squares estimators, the method selected for this data analysis was a derivative-free method. This method, described in detail in Appendix A, uses a modified "Gauss-Newton" method (to converge on a solution) so that both the size and the direction of steps can be determined simultaneously.

The model used in the iterative method is the following:

$$E = b_o + b_1 (V) + r [V_{t-1} - b_o - b_1 (E_{t-1})]$$

where

b_o and b_1	are regression coefficients
V_{t-1}	is operations lagged by t-1
E_{t-1}	is operational errors lagged by t-1, and
r	is correlation coefficient.

The output of the nonlinear regression analysis will produce a set of residual sum of squares which will give some idea of how well the data fits the predicted model values. These results would then give an indication of the size of the residual errors as a test of the estimated parameters.

To obtain these results, the nonlinear regression procedures were used to produce least-squares estimates of the parameters of the nonlinear model presented earlier. The procedure first performs a grid search to determine starting values for the parameters to be estimated, and then uses the prescribed iterative method to obtain its nonlinear least-squares estimations. The method regresses the residuals on the partial derivatives of the model with respect to the parameters, until the iterations converge.

B.3.2 Results for Pre-Strike Period

Using the first order lag coefficients for both variables, a nonlinear least-squares estimation was attempted using the modified Gauss-Newton iteration described above.

The results of this nonlinear regression procedure on the pre-strike tower data yielded the following model:

$$\text{errors} = -27.6738 + 8.8218\,(\text{tops*}) + r[(\text{tops*})_{t-1} + 27.6738 - 8.8218\,(\text{errors})_{t-1}]$$

with the asymptotic correlation (r) between the regression coefficients, b_o, and b_1 (refer to model), shown to be -0.9988, a strong negative correlation. The residual sum of the squares produced by the derivative-free model showed that the coefficients converge at the end of the third iteration. And, the residual errors which are produced by taking the difference between the observed and the predicted values of dependent variable (operational errors) fall close within a range of ±12.

For the pre-strike center data, the nonlinear least-squares estimations using the first order lag coefficients for each variable produced the model:

---

* Note: The notation "tops" in the above equation is the log of the tower operation.

$$\text{errors} = 222.7691 + 37.6894\ (\text{cops*}) + r[(\text{cops*})_{t-1} + 222.7691 - 37.6894\ (\text{errors})_{t-1}]$$

with the asymptotic correlation (r) between the regression coefficients, b_o, and b_1, shown to be -0.9999, a very strong negative correlation. The residual sum of the squares shows a convergence of coefficients after the third iteration. And, the residual errors fall close within a range of ±8.

The successful application of this nonlinear least-squares estimation procedure is not possible with the seven-point post-strike data as stated in the previous Section B.2.3.

B.4 Comparison of Pre-Strike and Post-Strike Results

In attempting to compare the results between the pre-strike and post-strike data analysis, it is important to be aware of limitations associated with such a comparison: the seven post-strike observations are considered only a small sample. With this condition stated, it was found that when comparing the sum of the squares across the products matrix, the cross-products between operational errors and operations were higher for the post-strike data than the pre-strike data. The sum of the squares of operations is almost 50 percent of the cross-products. The variability is somewhat higher in the post-strike data in the independent variable.

In the centers' data, the R^2 in the pre-strike data was 0.1973, barely significant at 0.05 level. The "t" ratio of the parameter estimate was 2.044, while in the post-strike data, the R^2 was only 0.0022. The cross-product is higher proportionately in the post-strike data than in the pre-strike data.

* Note: The notation "cops" in the above equation is the log of center operations.

In summary, the post-strike data show a greater variability than the pre-strike data, and they do not indicate any definite relationship between the errors and operations. The plots of pre-strike data are shown in Figures B-1 and B-2.

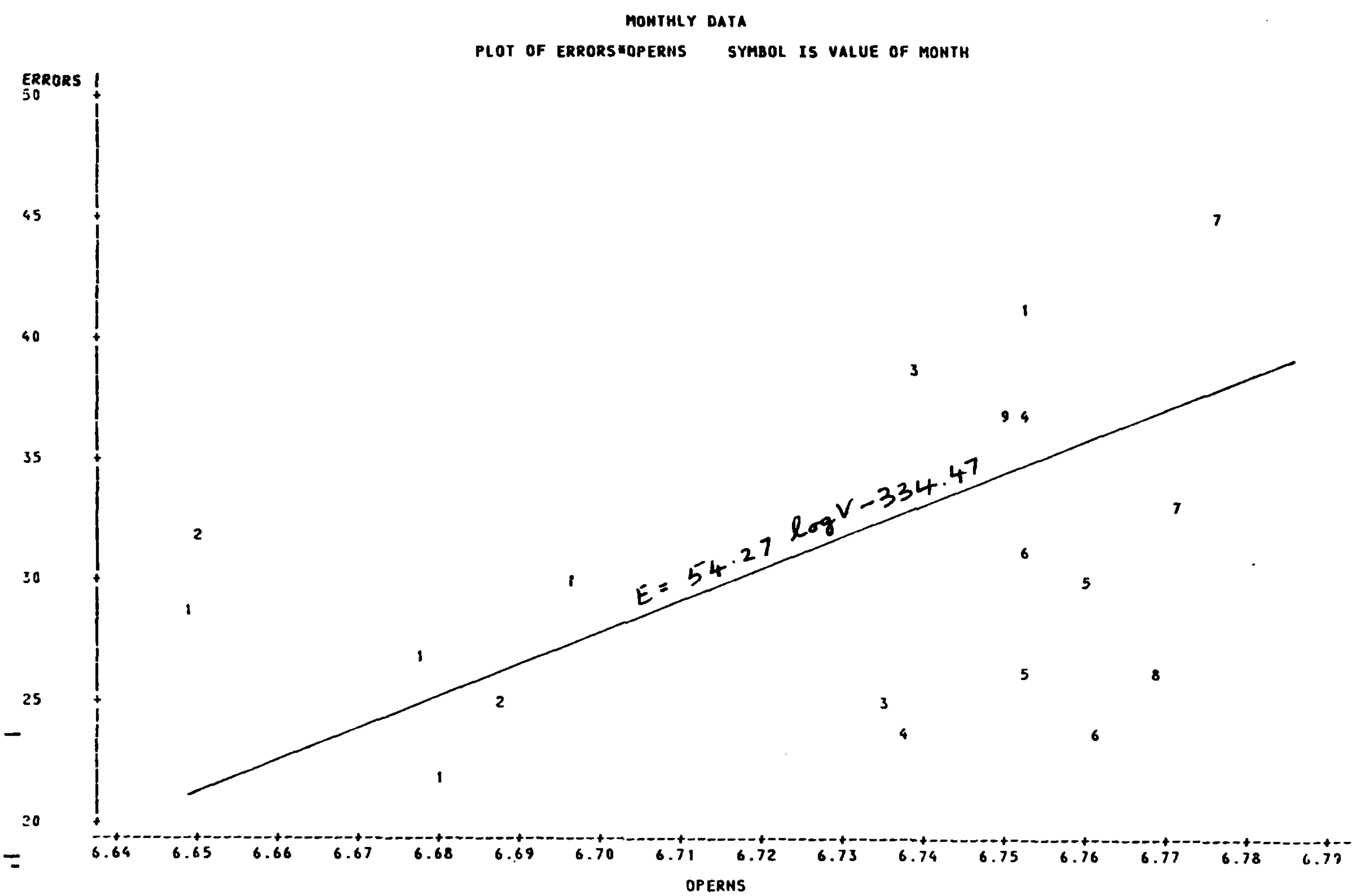


Figure B-1. Relationship Between Tower Operational Errors and Number of Operations Handled (Pre-Strike Period)

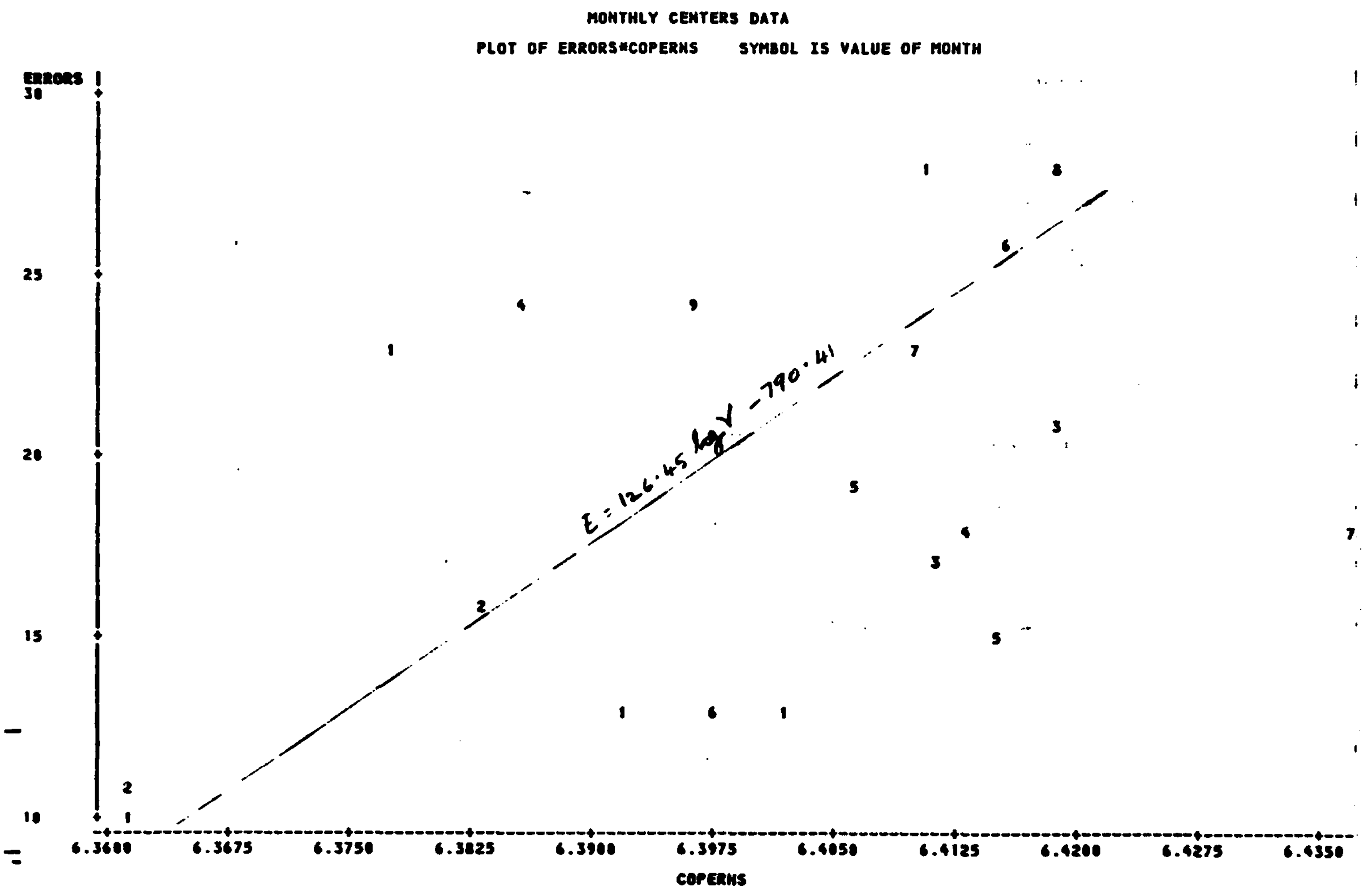


Figure B-2. Relationship Between Center Operational Errors and Number of Operations Handled (Pre-Strike Period)

APPENDIX C. OVERALL DATA AND TIME SERIES ANALYSIS

The objective of pooling pre- and post-strike data and conducting overall time series analysis is to examine whether there is any difference of relationship between operational errors and operations in the two periods. Note that this is only an indirect method of testing the difference existing in two periods, and is undertaken only because there was a lack of sufficient data in the post-strike period. If the difference in results obtained form overall data and pre-strike data analysis is negligible, then it suggests that the pre-strike and post-strike systems are alike and similar in safety. Both simple regression and autoregression models were fitted and analyzed with overall data, the results of which are presented below:

C.1 Overall Data Investigation

The results of the simple regression on the overall data group showed improvement in R^2 when compared to the regression results of the individual data groups. For the tower data, 58 percent ($R^2 = 0.5779$) of the variance in operational errors can be explained using the linear regression model, with a high value of 32.86, shown to be significant at the 0.0001 level.

Correspondingly, nearly 45 percent ($R^2 = 0.4474$) of the variance in center operational errors are explainable using the linear model, with the associated F ratio of 19.43 having a 0.0002 level of significance.

The linear models for each data group corresponding to their estimates of parameters determined from the single regressions, are as follows:

For Tower Data: E = 98.01 (Ops) - 629.65

For Center Data: E = 130.01 (Ops) - 813.31

Note that the model particular to the center data appears to be comparable to that model, shown earlier, from the pre-strike data regression.

Upon using the autoregression procedure on the overall tower data, the resulting autocorrelations (Table C-1) all were found to be positive (±), and to improve after the third order lag ($t=3$). The estimate of the b coefficient in the autoregression model, found to be 3.7834, is shown to be significant at the 0.0001 level using the t ratio. And, the covariance of the estimated b value with the dependent variable (E_t) is shown to be 0.21.

Applying the nonlinear derivative-free procedure, using the first order lag coefficients determined in the preceding autoregression, the estimates of the parameters appear to converge after the third iteration. The resulting model determined by the nonlinear regression was:

$$\text{errors} = 0.8239 + 4.0188\ (\text{tops}) + r\ [(\text{tops})_{t-1} + 0.8239 - 4.0188\ (\text{errors})_{t-1}]$$

with the asymptotic correlation (r) between the regressive coefficients, b_o and b_1, shown to be - 0.9067.

The residual errors were within a range of ±10, indicating that the predicted model data was close to the actual observations. And further, on examining the residual errors in the post-strike portion of the combined data, the values of the observed operational errors were consistently lower than the predicted operational errors as evidenced by the residuals.

Less dramatic results were shown with the center group of overall data (see Table C-2).

Table C-1. Results of Autoregression on the Overall Tower Data

Model: $E = bV_t + \varepsilon_t - a_1 \alpha_{t-1} - a_2 \alpha_{t-2} - a_3 \alpha_{t-3}$

1. Ordinary Least-Squares Estimates

Variable	DF	b-Values
(Intercept)	0	0
V_t	1	3.9791

2. Estimates of Autocorrelations

Lag	Covariance	Correlation
0	74.7246	1.0000
1	30.7375	0.4113
2	21.8423	0.2923
3	31.0877	0.4160

Bar Chart of Autocorrelations

```
-1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1
 |                    |********************|
 |                    |********            |
 |                    |******              |
 |                    |********            |
```

Table C-1 (Continued)

3. Estimates of Lag Coefficients

Lag	Coefficients	Std. Deviation	t ratio
1	-0.3168	0.1758	-1.8017
3	-0.3234	0.1758	-1.8394

Error Terms

Sum of Squares (SSE)	1294.163
Deg. of Freedom (DFE)	24
Mean Square (MSE)	53.9234
Root Mean Square (Root MSE)	7.3432

4. Estimate of b-Value

Variable	DF	b-Value	Std. Deviation	t Ratio	Approx.Prob.
(Intercept)	0	0	0		
V_t	1	3.7833	0.4537	8.337	0.0001

5. Covariance of b-Value

	Intercept	V_t
Intercept	0	0
V_t	0	0.2059

Table C-2. Results of Autoregression on the Overall Center Data

<u>Model</u>: $E_t = bV_t + \varepsilon_t - a_1 \alpha_{t-1} - a_2 \alpha_{t-2} - a_3 \alpha_{t-3}$

1. <u>Ordinary Least Squares Estimates</u>

Variable	DF	b-Values
Intercept	0	0
V_t	1	2.6296

2. <u>Estimates of Autocorrelations</u>

Lag	Covariance	Correlation
0	37.1163	1.0000
1	11.2881	0.3041
2	7.0555	0.1900
3	6.0588	0.1632

Bar Chart of Autocorrelations

```
-1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1

 |                    |********************|
 |                    |******              |
 |                    |****                |
 |                    |***                 |
```

Table C-2(Continued)

3. Estimates of Lag Coefficients

Lag	Coefficient	Std. deviation	t ratio
1	-0.2833	0.1890	-1.4984
3	-0.1093	0.1890	-0.5784

Error Terms

Sum of Squares (SSE)	861.9477
Deg. of Freedom (DFE)	24
Mean Square (MSE)	35.9144
Root Mean Square (Root MSE)	5.9928

4. Estimate of b-Value

Variable	DF	b-Value	Std. Deviation	t-ratio	Approx. Prob.
(Intercept)	0	0	0		
V_t	1	2.5815	0.2754	9.371	0.0001

5. Covariance of b-Values

	Intercept	V_t
Intercept	0	0
V_t	0	0.0758

C.2 Time Series Plots of the Data

The data for each pre-strike and post-strike period did not show a significant relationship. Therefore, it was decided to generate a time series plot of the overall data and to further investigate for any possible clues or relationship which may lead to a meaningful relationship. The series plots are shown in Figures C-1 and C-2.

Additional analysis on autoregression was performed and presented as a comparison of pre-strike and overall data in Figures C-3 and C-4. The plots show that most of the observations fall within the confidence regions.

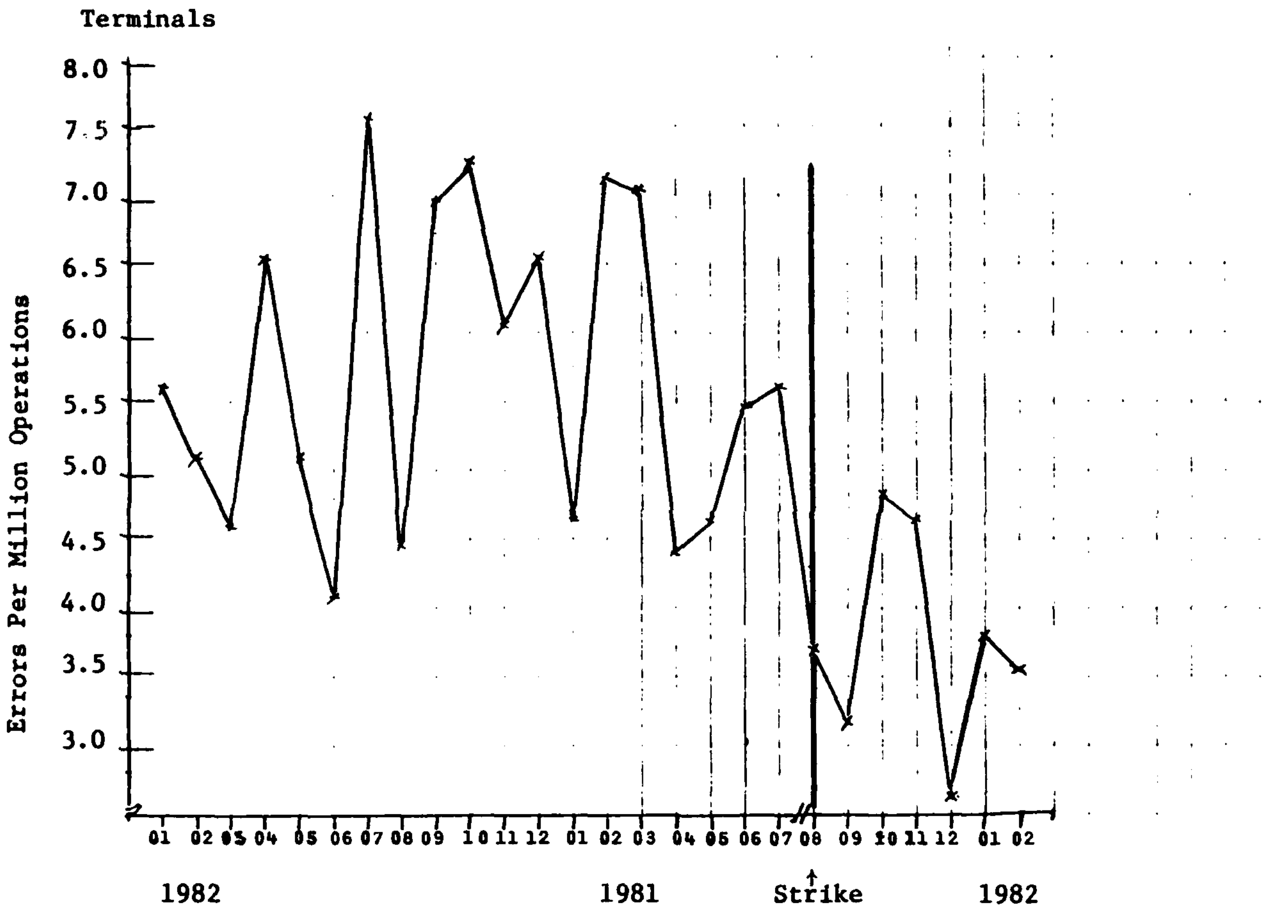


Figure C-1. Time Series Plot of Error Rates in Terminals

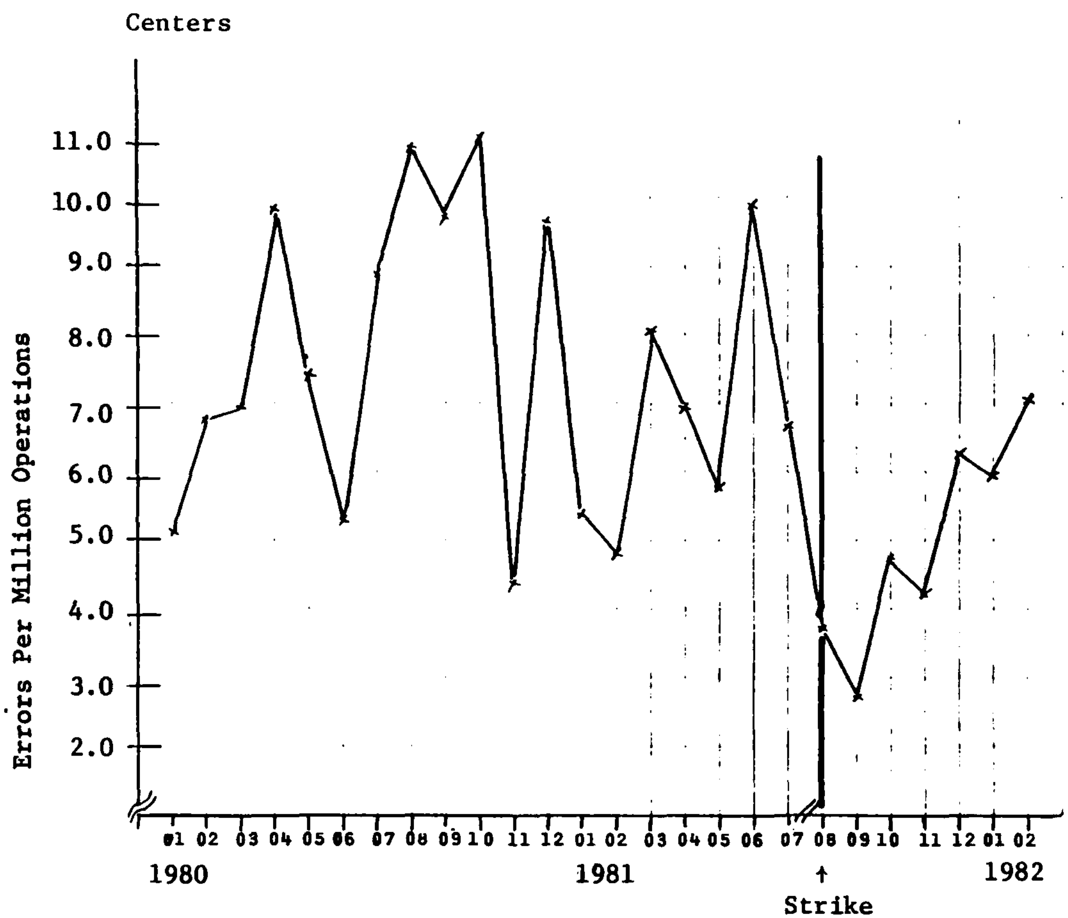


Figure C-2. Time Series Plot of Error Rates in Centers

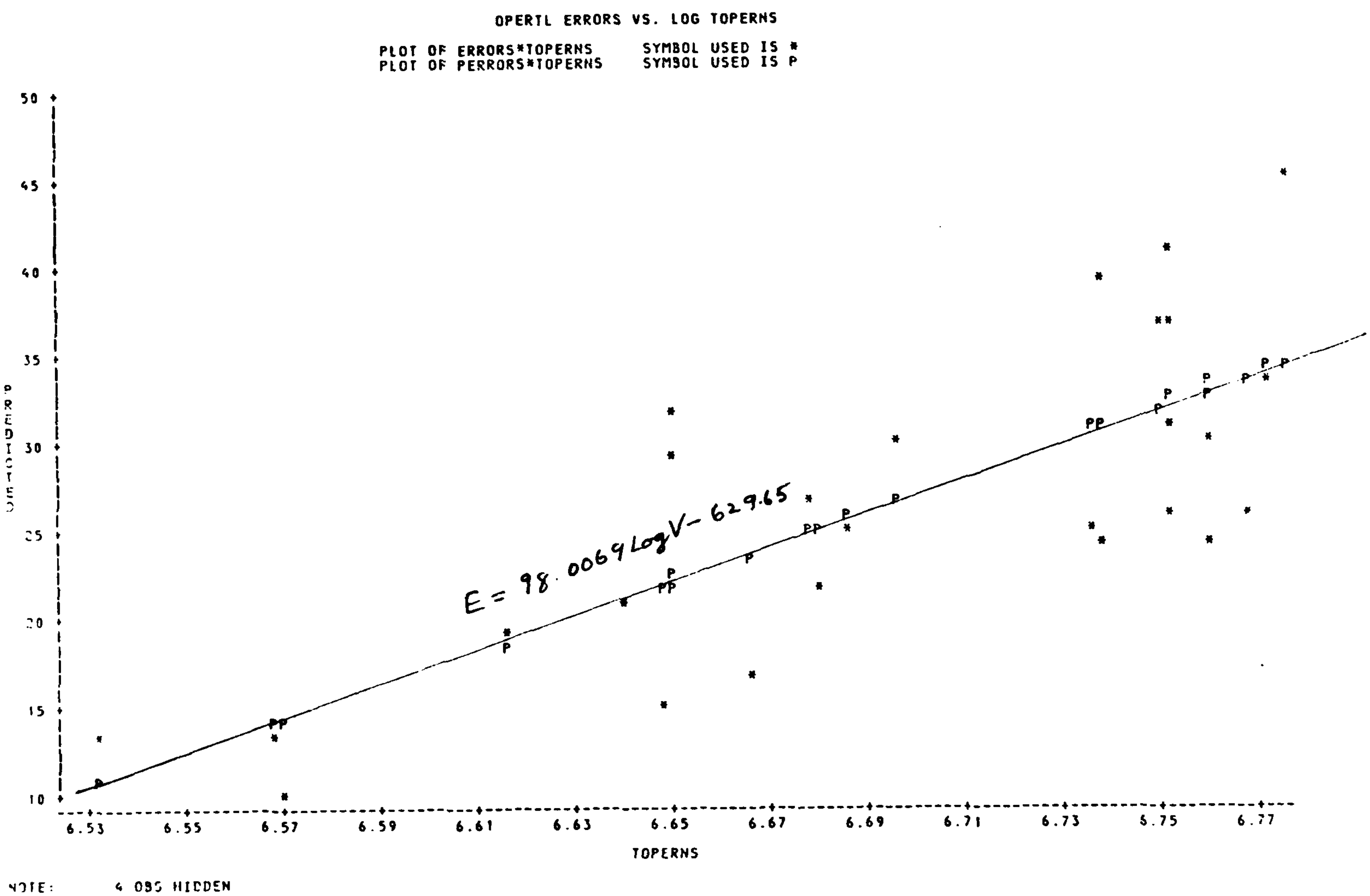


Figure C-3. Relationship Between Tower Operational Errors and Number of Operations Handled (Overall Pre- and Post-Strike Periods)

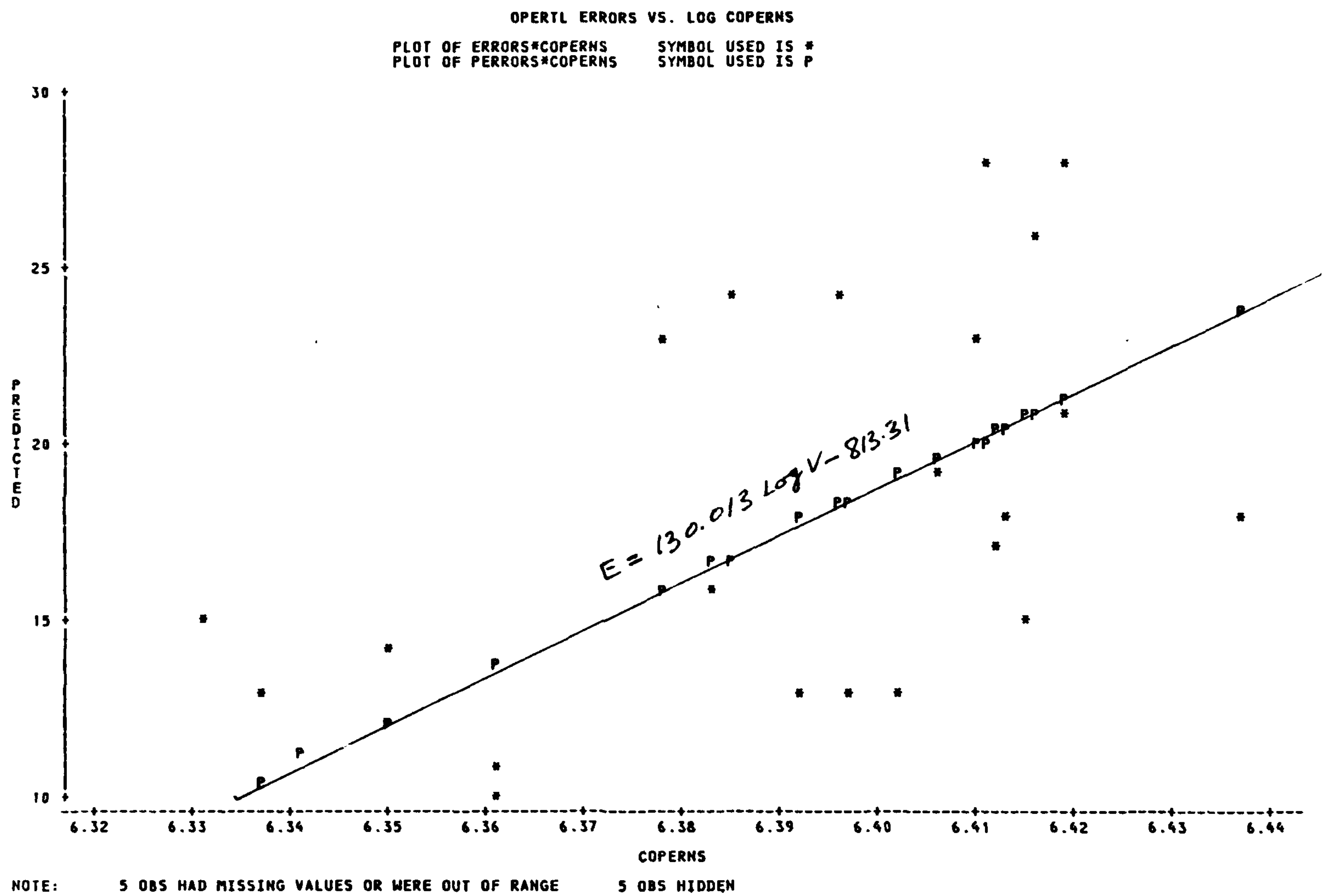


Figure C-4. Relationship Between Center Operational Errors and Number of Operations Handled (Overall Pre- and Post-Strike Periods)

C-3. Comparison of Pre-Strike and Overall Data

The comparison between the pre-strike and the overall data reveals some dramatic differences. The overall data indicate improvement in the correlation coefficient. In the towers, $R^2 = 0.5779$, and for the centers, $R^2 = 0.4474$. Both are significant. The sigma value was smaller in the centers data than in the towers data. The plots of the two along with confidence regions are shown in Figures C-5 and C-6.

In comparing the autoregression model of both pre- and post-strike data, it can be noted that the autocorrelations are all positive in all three of the time lags in the overall data. In the pre-strike data, the autocorrelations are negative in the first and second order time lags and change sign in the third order. When the autoregressive estimates were entered into the derivative-free nonlinear least-squares estimation procedure, it was found that the residual sum of squares converged after the third iteration, in both pre-strike and overall data.

The sum of the squares for the regression parameter is lower in overall data than the pre-strike data. Also in the pre-strike data, the confidence interval is wider than the overall data. And all the residuals post-data points in the overall data are negative, thus showing that the errors are lower than would be expected by the model. Since the model has a better fit in the overall data than the pre-strike data, it is reasonable to deduce that the system is at least as safe as in the pre-strike period.

The same is true for the centers. In the pre-strike data the autocorrelations were very low. The estimates of B value for the independent variable were significant at 0.0001 level in both pre-strike and overall data. The

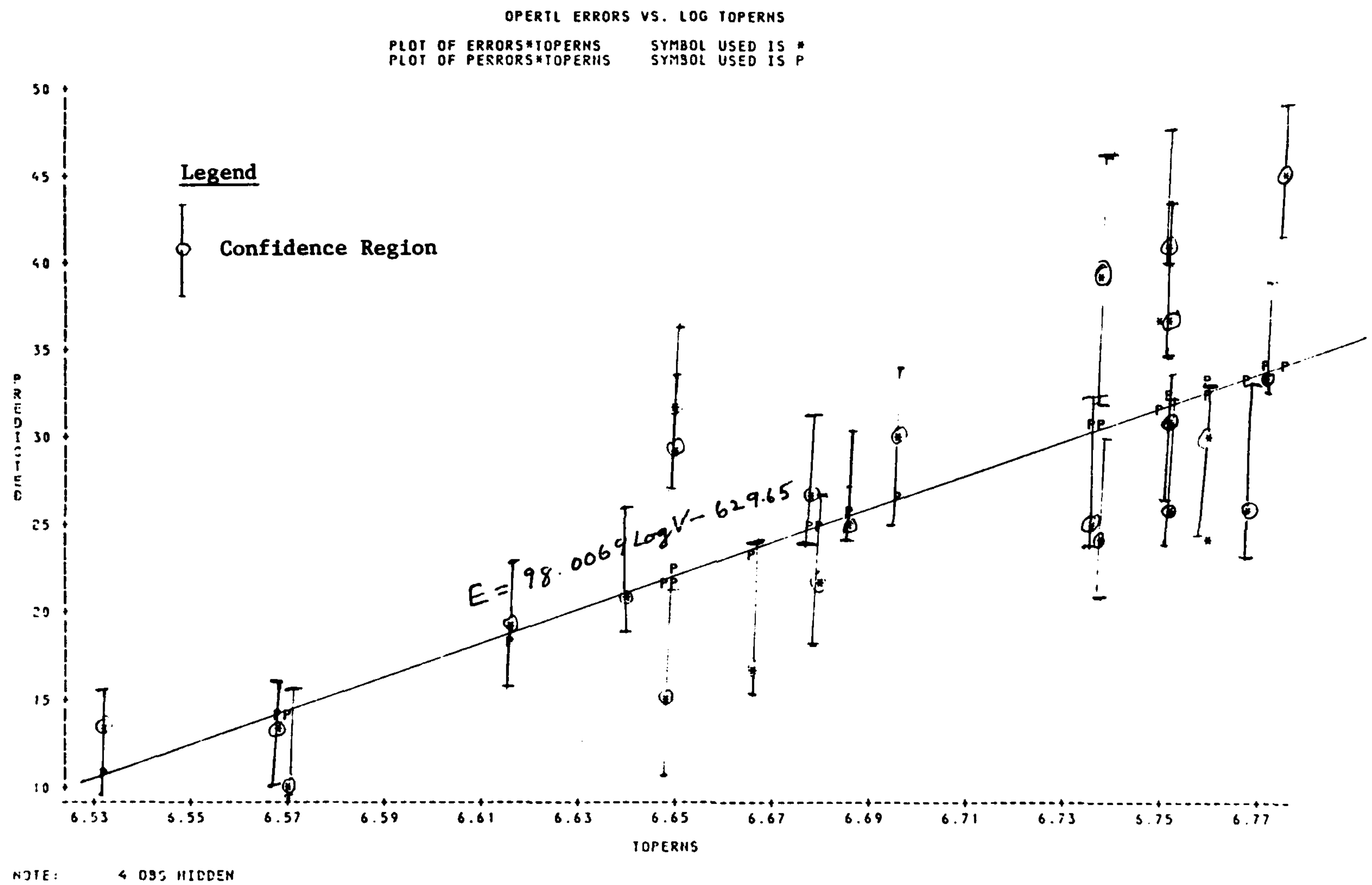


Figure C-5. Relationship Between Tower Operational Errors and Number of Operations Handled (Overall Pre- and Post-Strike Periods)

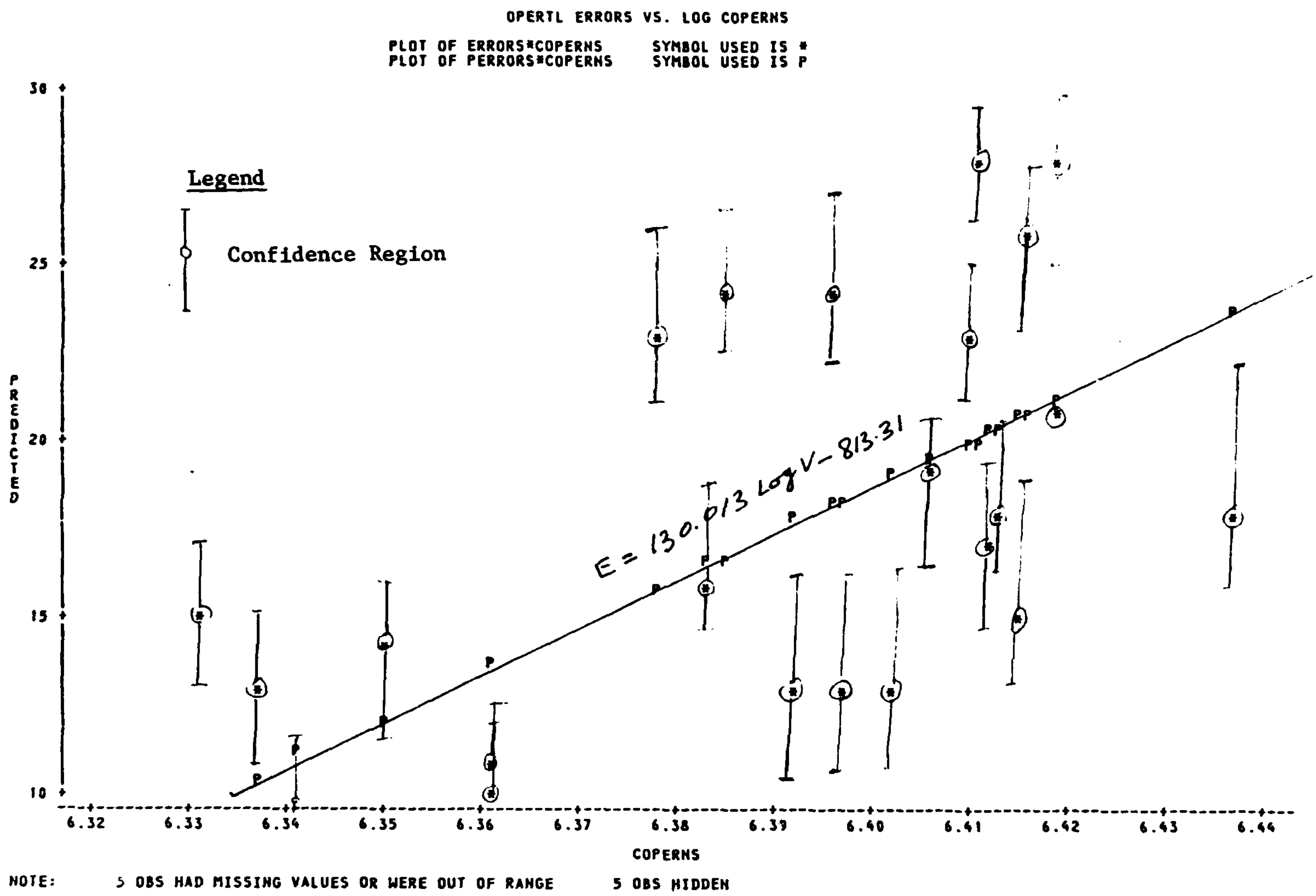


Figure C-6. Relationship Between Center Operational Errors and Number of Operations Handled (Overall Pre- and Post-Strike Periods) range of confidence interval was wider in the pre-strike data as shown before in the tower data. The residuals were again negative in the overall data. It would be reasonable to deduce, then, that the system is at least as safe in the post-strike period as in the pre-strike period. Figure C-7 shows typical statistical tests performed by Statistical Analysis System (SAS) computer programs.

```
                    MONTHLY  TOWERS PREPOST STRIKE DATA

                       DEPENDENT VARIABLE = ERRORS
                     ORDINARY LEAST SQUARES ESTIMATES
                        VARIABLE DF         B VALUE

                        INTERCPT  0               0
                        TOPS      1        3.979147

                        ESTIMATES OF AUTOCORRELATIONS
LAG  COVARIANCE  CORRELATION  -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1

 0      74.7246     1.000000  |                    |********************|
 1      30.7375     0.411344  |                    |********            |
 2      21.8423     0.292304  |                    |******              |
 3      31.0877     0.416031  |                    |********            |

                        PRELIMINARY MSE=     54.93218
                  ESTIMATES OF THE AUTOREGRESSIVE PARAMETERS
                  LAG   COEFFICIENT  STD DEVIATION       T RATIO

                   1    -0.31680506     0.17582849     -1.801785
                   3    -0.32342725     0.17582849     -1.839447

              SSE            1294.163
              DFE                  24
              MSE            53.92346
              ROOT MSE       7.343259


     VARIABLE DF          B VALUE  STD DEVIATION   T RATIO APPROX PROB

     INTERCPT  0                0              0
     TCPS      1   3.78338128574 0.453787785675      8.337      0.0001
                          COVARIANCE OF B-VALUES
                               INTERCPT        TOPS

                       INTERCPT       0           0
                       TOPS           0      0.2059

                          CORRELATION OF B-VALUES
                               INTERCPT        TOPS

                       INTERCPT       0           0




                    MONTHLY  TOWERS PREPOST STRIKE DATA
                               INTERCPT        TOPS

                       TOPS           0      1.0000
```

Figure C-7. Typical Statistical Tests

MONTHLY TOWERS PREPOST STRIKE DATA

NON-LINEAR LEAST SQUARES SUMMARY STATISTICS   DEPENDENT VARIABLE ERRORS

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	2	3751.42128944	1875.71064472
RESIDUAL	24	1291.02432586	53.79268024
UNCORRECTED TOTAL	26	5042.44561530	
(CORRECTED TOTAL)	25	2043.18500217	

PARAMETER	ESTIMATE	ASYMPTOTIC STD. ERROR	ASYMPTOTIC 95 % CONFIDENCE INTERVAL LOWER	UPPER
B0	-0.82386480	3.41074000	-7.86322950	6.21549989
B1	4.01876816	1.07472965	1.80065303	6.23688328

ASYMPTOTIC CORRELATION MATRIX OF THE PARAMETERS

	B0	B1
B0	1.000000	-0.906725
B1	-0.906725	1.000000

ALL ASYMPTOTIC STATISTICS ARE APPROXIMATE. REFERENCE: RALSTON AND JENNRICH, TECHNOMETRICS, FEBRUARY 1978, P 7-14.

Figure C-7. Typical Statistical Tests (Continued)

APPENDIX D. COEFFICIENT OF CORRELATION AND TEST OF PROPORTION

D.1 Coefficient of Correlation

The method used was a Pearson product-moment correlation coefficient. The formula used is as follows:

$$r = \frac{\left(\frac{\sum x_i y_i}{N}\right)^2 - \sum\sum x_i^2\, y_i^2}{\sqrt{\left(\frac{\sum x_i}{N}\right)^2 - \sum x_i^2}\;\sqrt{\left(\frac{\sum y_i}{N}\right)^2 - \sum y_i^2}}$$

where x_i = volume of operations

y_i = operational errors

D.2 Test of Proportions

This method uses Fisher's z distribution. The formula used is as follows:

$$Z = \frac{p_b - p_a}{\sqrt{pq\left(\frac{1}{n_b} + \frac{1}{n_a}\right)}}$$

where p_b = proportion or error rate in the pre-strike period

p_a = proportion or error rate in the post-strike period.

$$p = \left(\frac{P_a + P_b}{n_a + n_b}\right)$$

$$q = 1 - p$$

$$\Pr\ \{ 1.96 \leq Z_i < Z_u \} = 0.05$$

APPENDIX E. PLOTS OF OPERATIONAL ERRORS BY WEEK

Figures E-1 and E-2 show the time series plots of operational errors by week in the terminals and centers. The difference between the pre-strike and post-strike operational errors in the terminals is larger than corresponding errors in the center. When the operational errors are combined in the terminals and centers, the plots show that the pattern of errors is similar in the post-strike period to that of the pre-strike period. Post-strike errors show lower level than pre-strike period errors. However, when the data are plotted using the methods of moving average with a step of three, the pre-strike errors show smoother level than the post-strike errors. These plots are shown in Figures E-3 and E-4 respectively.

The operational error rates for the terminals and centers are shown in Figures E-5 and E-6 by week. It is evident that the post-strike error rates are lower than the pre-strike error rates. The corresponding mean level is lower in the post-strike period than in the pre-strike period. The two points which are circled are asymptotic points. In the center the data range is wider than that of the terminals.

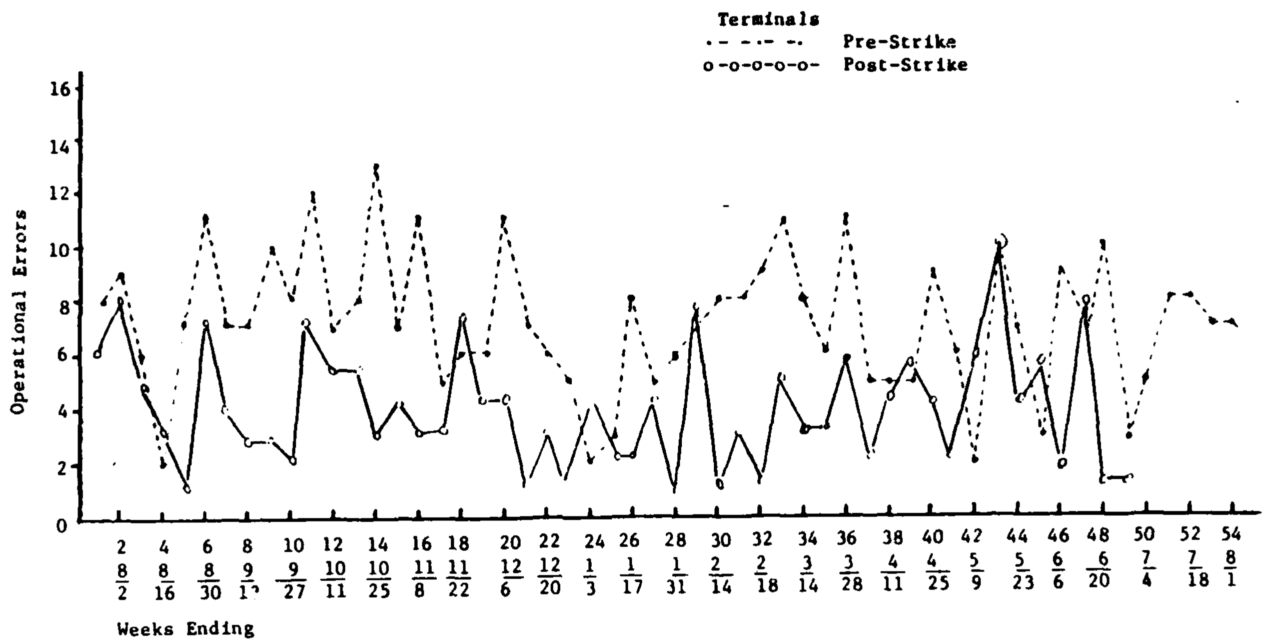


Figure E-1. Time Series Plot of Operational Errors by Weeks in Terminals

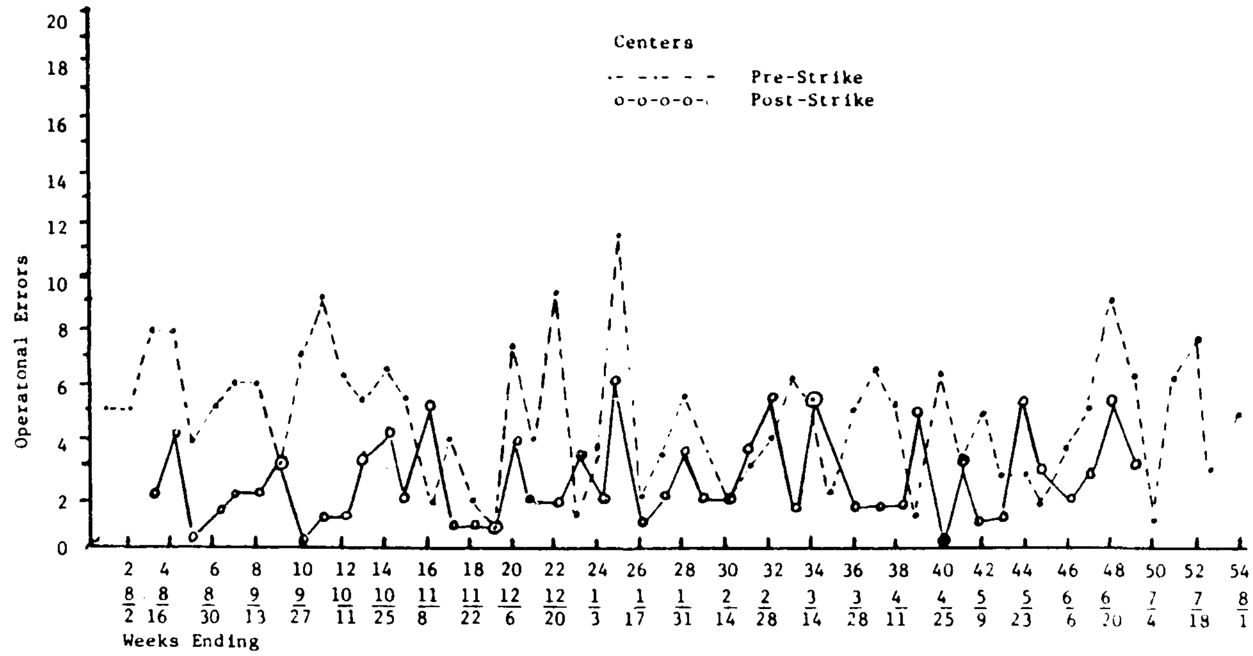


Figure E-2. Time Series Plot of Operational Errors by Weeks in Centers

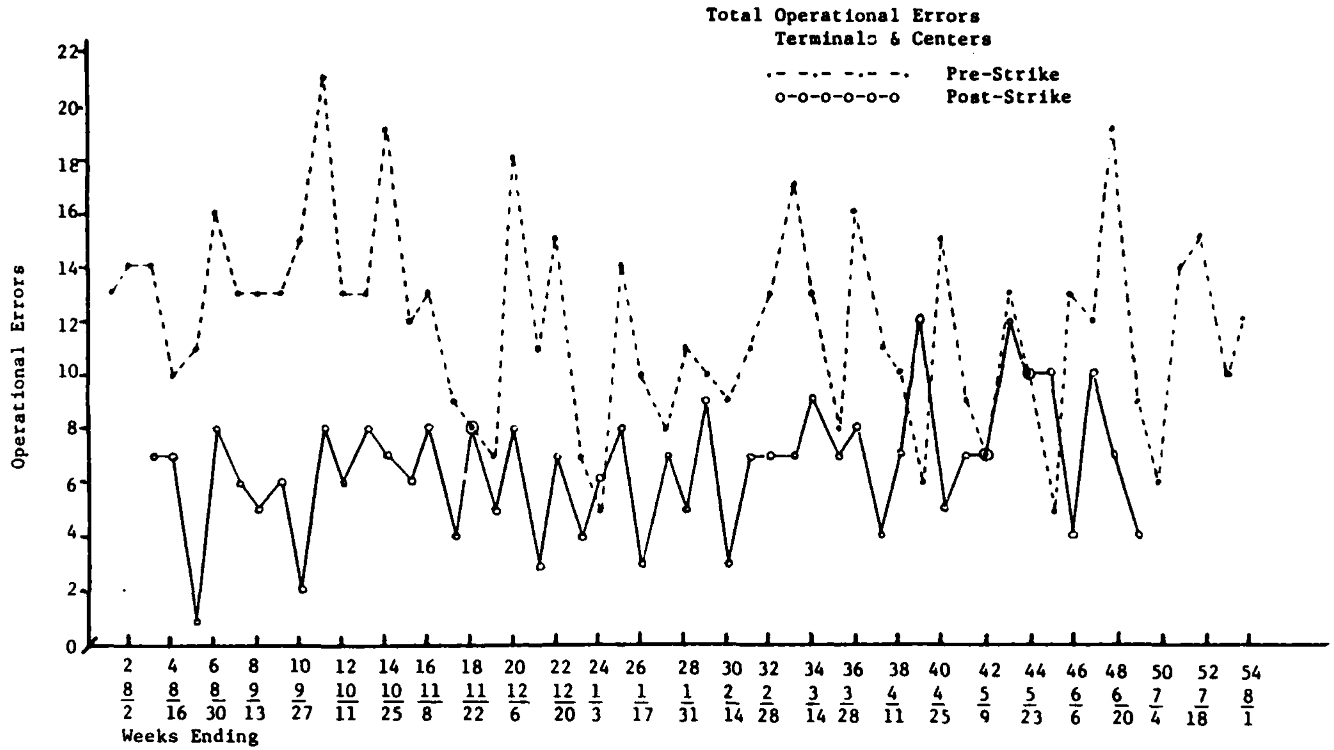


Figure E-3. Time Series Plot of Total Operational Errors by Weeks

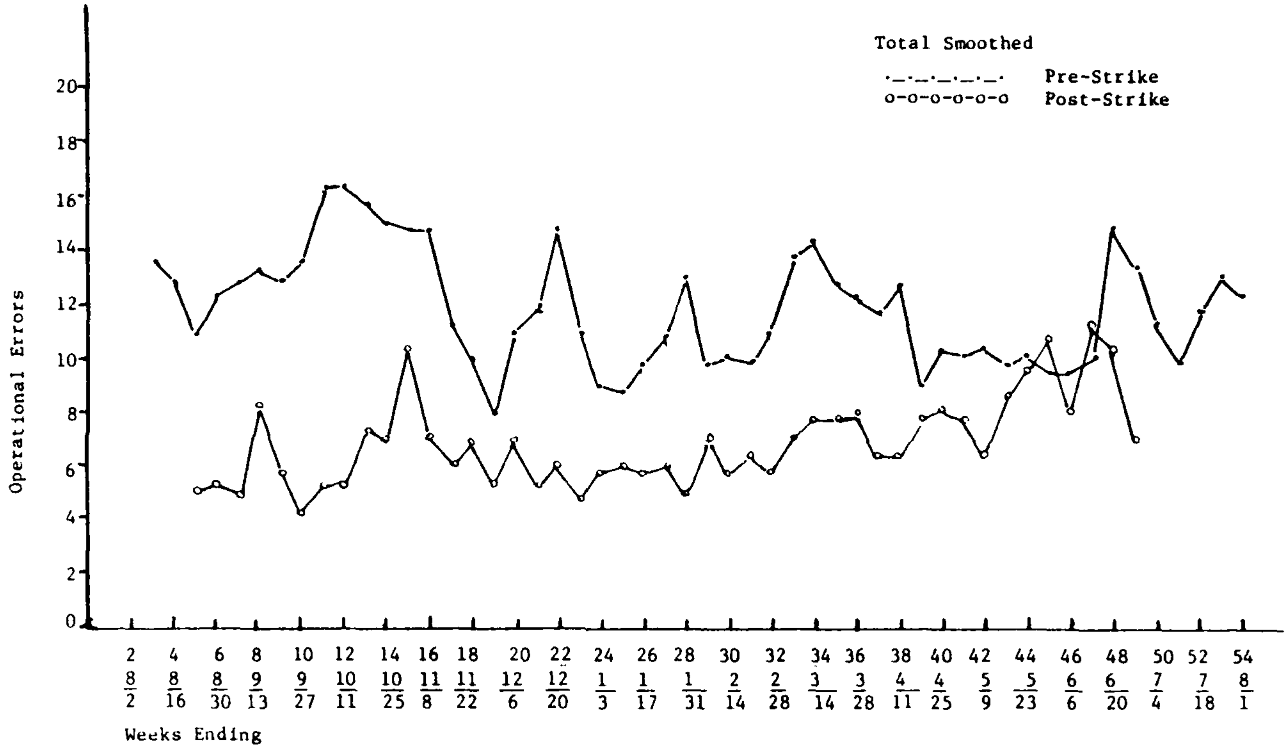
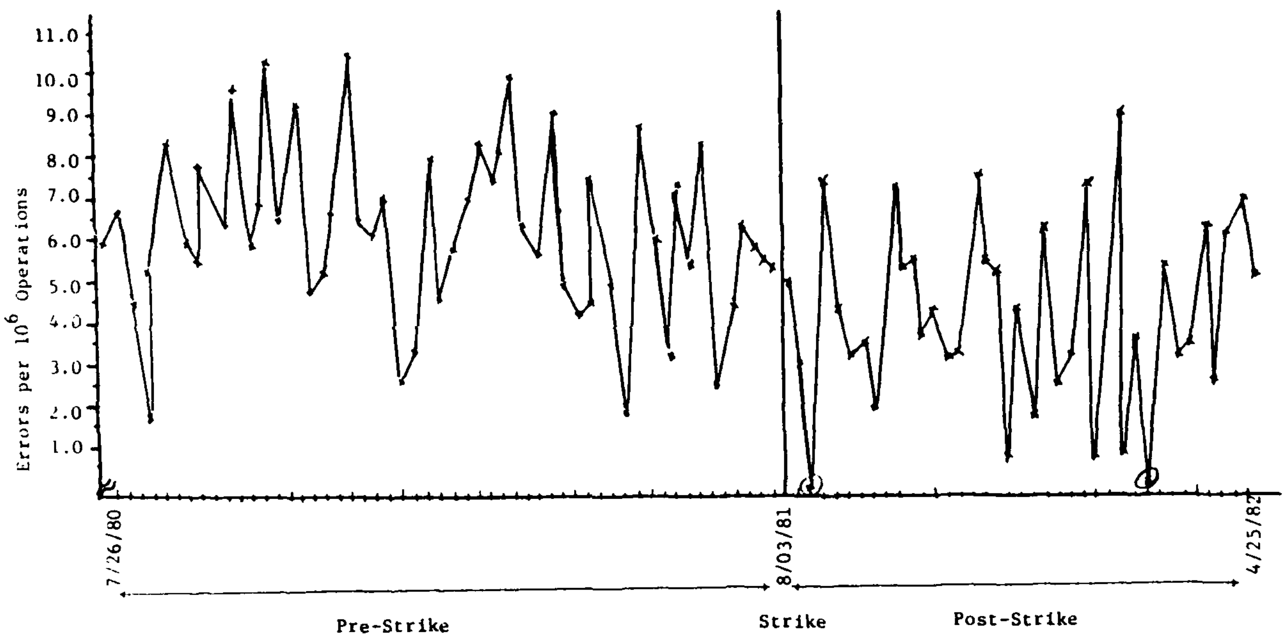


Figure E-4. Smoothed Time Series Plot of Total Operational Errors by Weeks



● = out of range

Figure E-5. Time Series Plot of Operational Error Rates by Weeks in Terminals

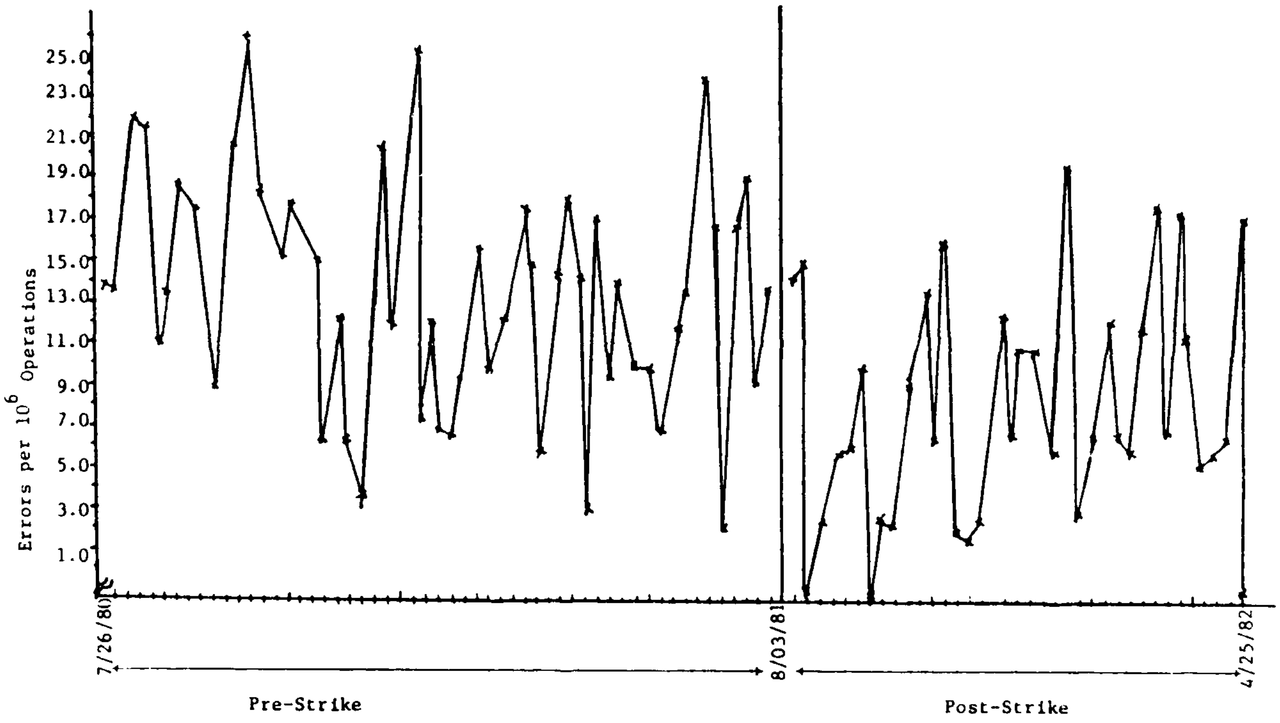


Figure E-6. Time Series Plot of Operational Error Rates by Weeks in Centers

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